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THE ERECHTHEON, ATHENS.

A view taken at night showing the beautiful effect obtained by the use of G.E.C. floodlights.

G.E.C. Journal

VOL. III. NOVEMBER, 1932. No. 4.

Floodlighting.

PART I.

By THOMAS E. RITCHIE, A.M.I.E.E.
Chief Illuminating Engineer of The General Electric Co. Ltd.

THE floodlighting of London's famous buildings carried out as a signal of welcome to the Home and Foreign delegates to the Triennial International Illumination Congress, which met in London for the first time last September, enabled London to be seen as never before. It also afforded illuminating engineers a unique opportunity of studying critically the problems relating to the illumination on an extensive scale of buildings differing widely in size and character, and ranging in age from the days of William the Conqueror to the latest addition to the architectural features of Millbank, which at the time of the Congress was actually unfinished.

Apart, possibly, from the Thames Embankment with its world renowned lighting, and such homes of the electric sign as Piccadilly Circus, London is not a brightly illuminated city. Its main streets still depend too much on the shopkeeper for light, while floodlighting at ordinary times is almost unknown. It was to be expected therefore, that the spectacular transformation of many of its smoke begrimed buildings into fairy castles and palaces would constitute something in the nature of an outstanding attraction. It was not anticipated, however, that there would be such an extraordinary display of interest and appreciation by all classes of the community as that which manifested itself in so spontaneous and overwhelming a manner on the opening night. Even more striking is the fact that the interest was sustained in unabated measure throughout the whole of the month during which the display was continued, the crowds which gathered nightly before the principal floodlighted buildings, such as Buckingham Palace (one of the many prominent buildings floodlighted by the G.E.C.) being as dense at the end of September as on the opening night.

The display gave rise to a considerable amount of comment, and criticisms, both favourable and the reverse, were freely published in the lay press and technical journals. While some of these views can be dismissed as being unbalanced and prejudiced, there were many restrained and reasonable expressions of opinion which proved definitely stimulating and constructive.

It is therefore proposed in this article to deal with these criticisms and thereby to show how floodlighting, properly and scientifically applied, can bring out the architectural beauty of buildings by night.

The chief objections, or at any rate those most frequently expressed, and to which, therefore, the greatest prominence has been given, may be summarised as follows :—

(*a*) The lighting is unnatural.

(*b*) Architectural character is destroyed by reason of the effects of light and shade differing from those characteristic of daylight.

In Part I *of this article various criticisms which have been levelled at floodlighting are dealt with in such a way that the fundamental principles underlying this new science are clearly demonstrated.*

Part II, *to be published in an early issue of the G.E.C. Journal, will describe the actual methods adopted to attain certain desirable effects.*

(*c*) Insufficient attention is paid to the condition of the surfaces.
(*d*) Fenestration is ignored.
(*e*) Roofs are neglected, with the result that buildings appear unfinished.
(*f*) The sense of depth is lost.

Such considerations have so vital a bearing upon the practical application of the principles underlying successful installations of floodlighting that they may profitably be examined in detail.

(*a*) "*The lighting is unnatural.*" If by this is meant that anything resulting from man's effort, rather than from Nature's, is unnatural and is, therefore, necessarily wrong, lacking in beauty, or otherwise undesirable, then it must frankly be conceded that floodlighting suffers from the disability common not only to all forms of artificial

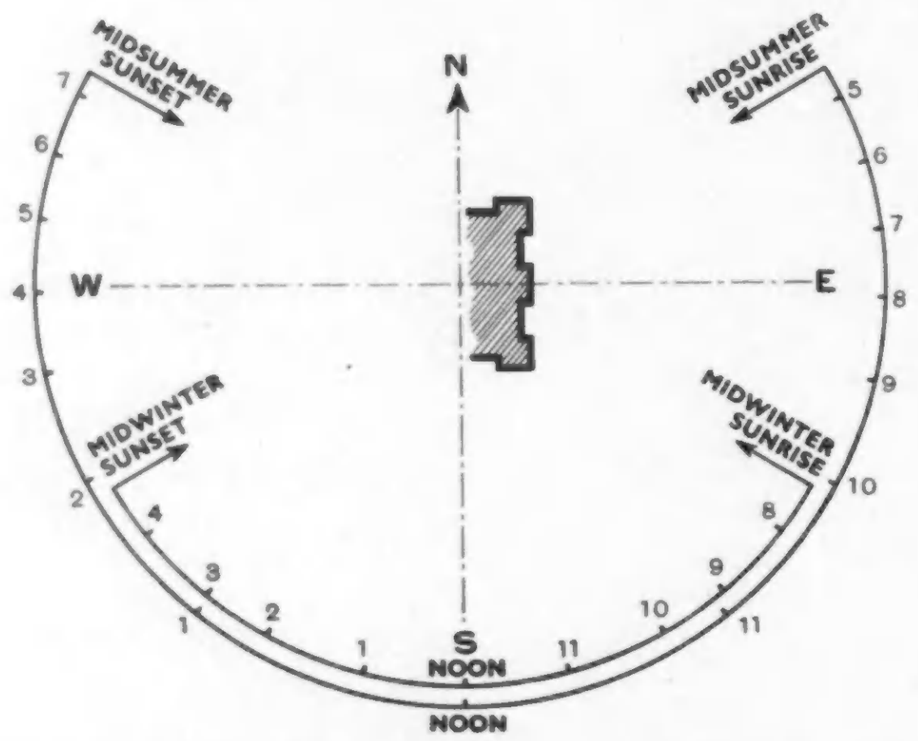

Fig. 1.—Diagrammatic representation of the arcs made by the sun during summer and winter.

lighting, but to man's creative handiwork as a whole. Considered from this standpoint, the very buildings, the illumination of which we are discussing, are themselves unnatural. The furniture, carpets, wall-coverings and pictures which they contain are without exception unnatural, whilst it is equally unnatural for us either to warm them in winter or to cool them in summer.

It is impossible for us in these islands to see the masterpieces of, for instance, Turner, Tintoretto or Velasquez, by the natural light under which many of them were painted, or, in the case of many of us, even by our own possibly less perfect daylight. Are we, therefore, on the score that such illumination is unnatural—and presumably by implication wrong—to be debarred from appreciating and enjoying their beauty by artificial light? Must we discard the beautiful spectacles provided by our masters of stage-craft, and revert to the crudities of the open air theatre of Shakespeare's day, merely because our present day productions are not only revealed to us but are enhanced in beauty by the skilful use of artificial light? We must preserve a reasonable sense of proportion, and appreciate that things which are artificial are not by any means necessarily things which are wrong; we should remember that the supposedly unnatural things of yesterday are the perfectly natural and usual things of to-day. Briefly, we must distinguish correctly between "unnatural" and "artificial." The fact that a pleasing effect is created by artificial means need never, and very rarely does, detract from either its rightness or its beauty. Lovely as is Nature's handiwork, there are few of us who would willingly suffer even the partial withdrawal of the manifestations of beauty which come into our lives through the medium of things artificial.

(*b*) "*Architectural character is destroyed by reason of the effects of light and shade differing from those characteristic of daylight.*" This particular objection is undoubtedly more widespread than any other. That this should be so is more than remarkable. The sun is relatively a moving body, and to describe as "characteristic" the ever-changing shadow effects produced by a light varying, as does daylight, in direction, intensity and diffusion to such a degree, is surely both inappropriate and misleading.

The suggestion that there is a right direction from which daylight should fall upon a building, and that in designing his facade the architect had this consciously in view, is not only disproved by a cursory study of the play of light and shade upon the face of any particular building over even a few hours, but has been publicly denied by at least one prominently successful architect, who went so far as to add that in floodlighting he did not consider that it was necessary, or even desirable, to imitate daylight effects.

The extent to which the appearance of the facade of a building viewed from a given standpoint is modified by changes in the natural lighting is much more pronounced than is commonly supposed. In a building facing South, for instance, the complete reversal of shadow resulting from the change from the angular side lighting of the early morning sun, to the equally directional and diametrically opposite effect produced when the sun is setting, is sufficient entirely to alter the impression received. Moreover, when it is remembered that the angle at which sunlight strikes a building varies from an almost horizontal to an almost vertical direction; that the angle from which, in most cases, the building must of necessity be viewed varies to an almost equal extent, and that, in this country at all events, diffused lighting is as common as sunshine, it will be appreciated that the determination by the illuminating engineer of the particular direction from which

a given building should be floodlighted is, apart altogether from such physical limitations as may be encountered, a matter involving not only careful thought, but considerable practical experience.

In fig. 1 is reproduced a diagrammatic representation, originated by Mr. Walter D. Popham, the well-known landscape architect, which will tend to make clearer the point under discussion. The larger curve shows the arc made by the sun from sunrise to sunset in summertime, and the smaller curve that in winter. By placing on the diagram, and correctly orientating in relation to the points of the compass, a small scale plan of a building, it is possible to observe the direction from which the sun's rays will shine upon the facade at any hour of the day between its rising and its setting. Consider, for instance, a building facing East, and viewed from a point forward of, and in the centre of, its front. The facade will, during the early hours of a mid-summer day, be strongly lighted from a direction to the right of its centre, with, as a consequence, pronounced shadow on the left of any projecting architectural features. In mid-winter this effect is reversed. Left-hand shadows are non-existent for the reason that, as the diagram shows, such of the sun's rays as reach the facade directly can come only from the left-hand side. The play of light upon a facade having any other aspect can similarly be studied.

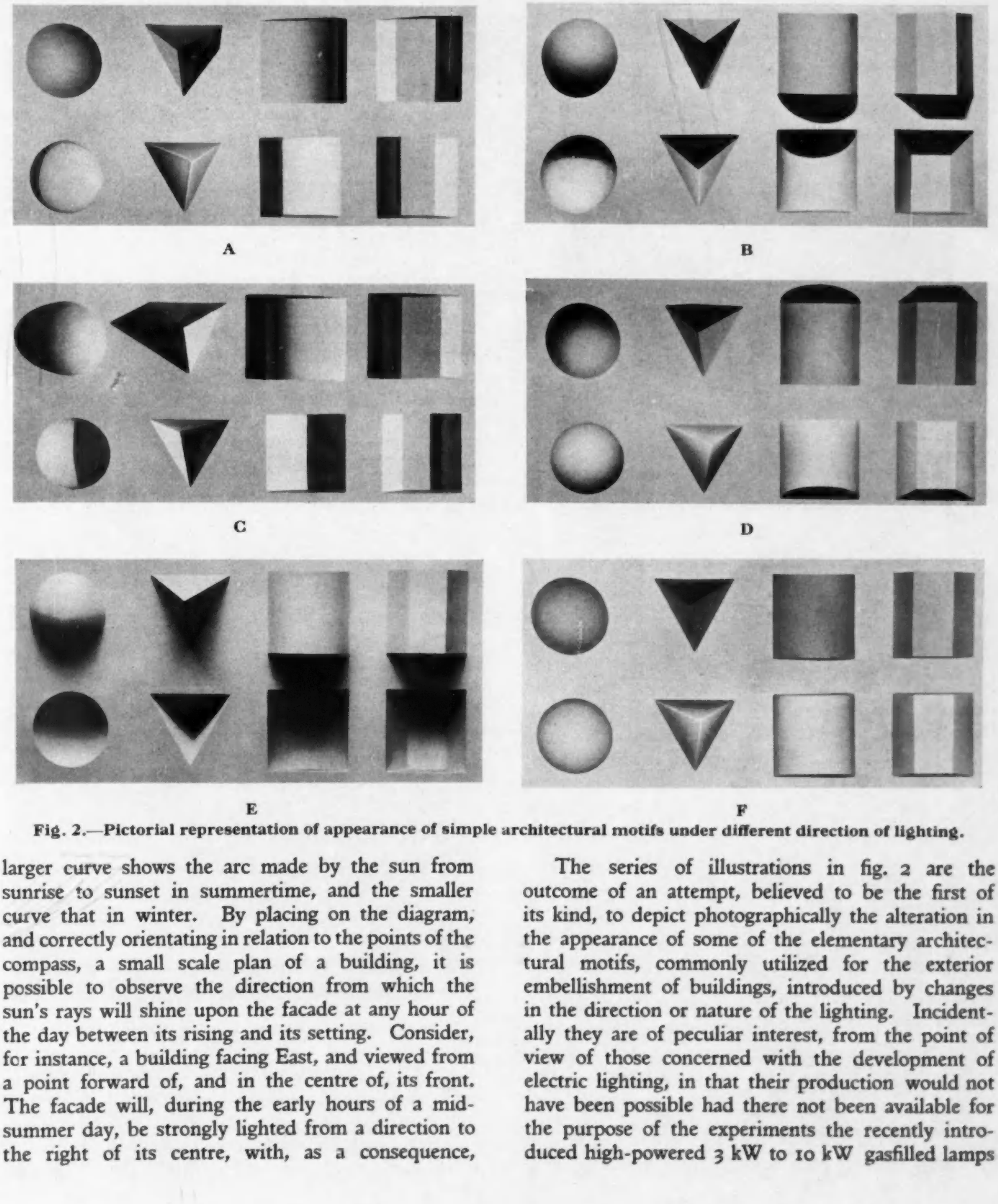

Fig. 2.—Pictorial representation of appearance of simple architectural motifs under different direction of lighting.

The series of illustrations in fig. 2 are the outcome of an attempt, believed to be the first of its kind, to depict photographically the alteration in the appearance of some of the elementary architectural motifs, commonly utilized for the exterior embellishment of buildings, introduced by changes in the direction or nature of the lighting. Incidentally they are of peculiar interest, from the point of view of those concerned with the development of electric lighting, in that their production would not have been possible had there not been available for the purpose of the experiments the recently introduced high-powered 3 kW to 10 kW gasfilled lamps

and projector fittings used for the creation of sunlight effects in cinema studios. After initial attempts under natural daylight, which were ultimately relinquished owing to the vagaries of the English climate, the experiments were continued in a sufficiently extensive and lofty studio possessing the advantage of highly directive lighting of unvarying and sufficient intensity, operating under controlled

Fig. 3.—Illustrating the effect of skilful floodlighting on a group of statuary.

conditions. A model was constructed containing upon its face a series of projections and depressions arranged in pairs corresponding exactly in dimensions and presenting to the observer in, for example, the hemisphere and half cylinder shown, convex and concave surfaces identical in curvature and area. The illustrations lettered A to F show the appearance of the model under different types of lighting.

Example (A) shows the effect produced by approximately horizontal lighting from a single source of small dimensions located at the left-hand side, such as that produced by early morning or late evening sunshine; (B) that produced by similar lighting directed from above, and slightly to the left of the centre, such as is given by the sun at about the hours of 11.0 a.m. and 2.0 p.m.; (C) that produced by equally bright sunshine from the right-hand side, but with the sun at an altitude greater than would prevail in example (A); and (D) that resulting from floodlighting from below, using in this case a number of light sources such as would generally be employed in practice.

Example (E), which should be carefully compared with (B), is interesting as showing the effect produced by totally indirect and exceedingly diffused lighting from directly overhead, such as is usually experienced on a normally bright day in the absence of direct sunshine. Example (F) is also of special interest, as the result shown is a deliberate attempt to reproduce the excessively flat and uninteresting lighting which obliterates all architectural charm. Flat lighting of this type is quite unsuitable if any sense of roundness and solidity is to be retained. It has its uses, but the revealing, or the creation of the illusion of a third dimension is not one of them. Such shadows as exist stream directly away from the observer and are hidden from view by the objects behind which they lie, and the result, as will be seen, is much less interesting than when any other type of lighting is employed. That quite the reverse effect can be secured by more skilful treatment is apparent from the illustration reproduced in fig. 3, in which a group of statuary has been floodlighted by G.E.C. engineers.

(c) "*Insufficient attention is paid to the condition of the surfaces.*" The soundness of this criticism cannot be denied. Its accuracy and fairness was, and is, self-evident, and illuminating engineers and owners of floodlighted buildings should be grateful to those who focussed attention upon so vital a matter. That the griminess of facades carrying the

Fig. 4.—Pitman House, London, during cleaning operations.

accumulated dirt of half a century or more, should, night after night, continue to be thrust under the notice of the passer-by, can only be due to the failure of all concerned to appreciate both the ease, and cheapness with which the necessary

cleaning can be carried out by modern methods, and from the point of view of pleasing and efficient floodlighting, the great economy which can be secured by an expenditure which is relatively very small.

The success or failure of floodlighting is largely dependent upon the amount of the light directed upon the surface of a building or object, which is reflected back into the eyes of an observer. In the case of a white or light coloured surface, the proportion may be large, say from 60 to 80 per cent. In the case of a black or dark coloured surface, the proportion is very considerably less, and if, in addition to being dark in colour, the surface is matt in texture, as is the case with stone, it may be as low as from 5 to 10 per cent. The proportion, whatever it may be, of the total incident light which is reflected by a given surface is known as its reflection factor, and the higher this is, or can be made, the more easily and more cheaply can a desired effect be secured by the lighting engineer.

Whether as an outcome of the criticisms to which we have referred or not, the fact remains

Fig. 5.—Magnet House, London, showing different reflection factors during cleaning.

that during the past year more attention has been paid, and is still being paid, to the condition of the exterior of buildings than ever before. In London especially, evidence of activity in this direction is visible on many sides, and advantage has been taken of the opportunities thus provided to secure accurate scientific data which has not hitherto been available. In figs. 4, 5 and 6 are reproduced photographs of typical buildings in course of renovation. In each case the average reflection factor was determined as the mean of a number of carefully conducted photometric measurements made in dry weather immediately before the cleaning of the portions involved was begun, and as soon after its completion as the surface of the cleansed portion was thoroughly dry. The building

Fig. 6.—The City Temple, London; cleaning operations increased the reflection factor from 6.4 to 47 per cent.

shown in fig. 4 is of red brick. As will be seen, the reflection factor was raised by cleaning from 11 per cent to 39 per cent. The facade of the building illustrated in fig. 5 is of Portland Stone, the reflection factor of which was, by the same means, raised from 21 per cent to 64 per cent. That the examples cited are not in any sense extreme is demonstrated by the case of the stone building illustrated by fig. 6, in which the factor was increased from 6.4 per cent to 47 per cent.

Turning from the general to the particular, it is of interest to consider the result which would be obtained by the improvement in reflection factor of an actual installation. The floodlighting of the headquarters of the Institution of Electrical Engineers is shown by the untouched night photograph reproduced in fig. 7. The bulk of the facade is of red brick, having an average reflection factor

of 7 per cent. Twenty-six floodlights are employed, each equipped with a single lamp of 1,500 watts, making an aggregate total load of 39 kW. Unfortunately, it was impossible in the time available to have the front steam-cleaned prior to the installation of the flood-lighting. Had such renovation been possible there is no reason to suppose that an improvement in the reflection factor of from 11 to 39 per cent as shown in fig. 4 would not have resulted. Had this proved possible, substantially the same effect could have been obtained from an expenditure of 7 kW. In other words, whilst the number of floodlights used would have remained unaltered, for the reason that this is dependent upon the area which it is required to illuminate, the wattage of each of the lamps could have been reduced from 1500 watts to 300 watts with a saving of four-fifths of the present current bill.

Fig. 7.—The Institution of Electrical Engineers, London.

An unusually interesting instance of the importance of the reflection factor of wall surfaces is to be found in the extent of its influence upon the efficiency of the glazed brick walls of the light wells, which constitute so essential a feature of modern buildings. Fig. 8 shows a portion of the surface of the white glazed brick walls of such a well after only one year's service. The portions adjacent to the rainwater pipe, which could be reached from the windows, were, prior to the taking of the photograph, carefully washed in such a manner as to avoid disturbing the remainder of the soiled surface. It will be noticed that even after the lapse of so short a time, the efficiency of the walls as reflecting surfaces has fallen roughly to half its original value. Important as is such a loss from the point of view of the provision of adequate daylight, it is of even greater moment when the question of artificial lighting is involved. It has been found by experience that the illumination of the walls of such wells, not only during the hours of darkness

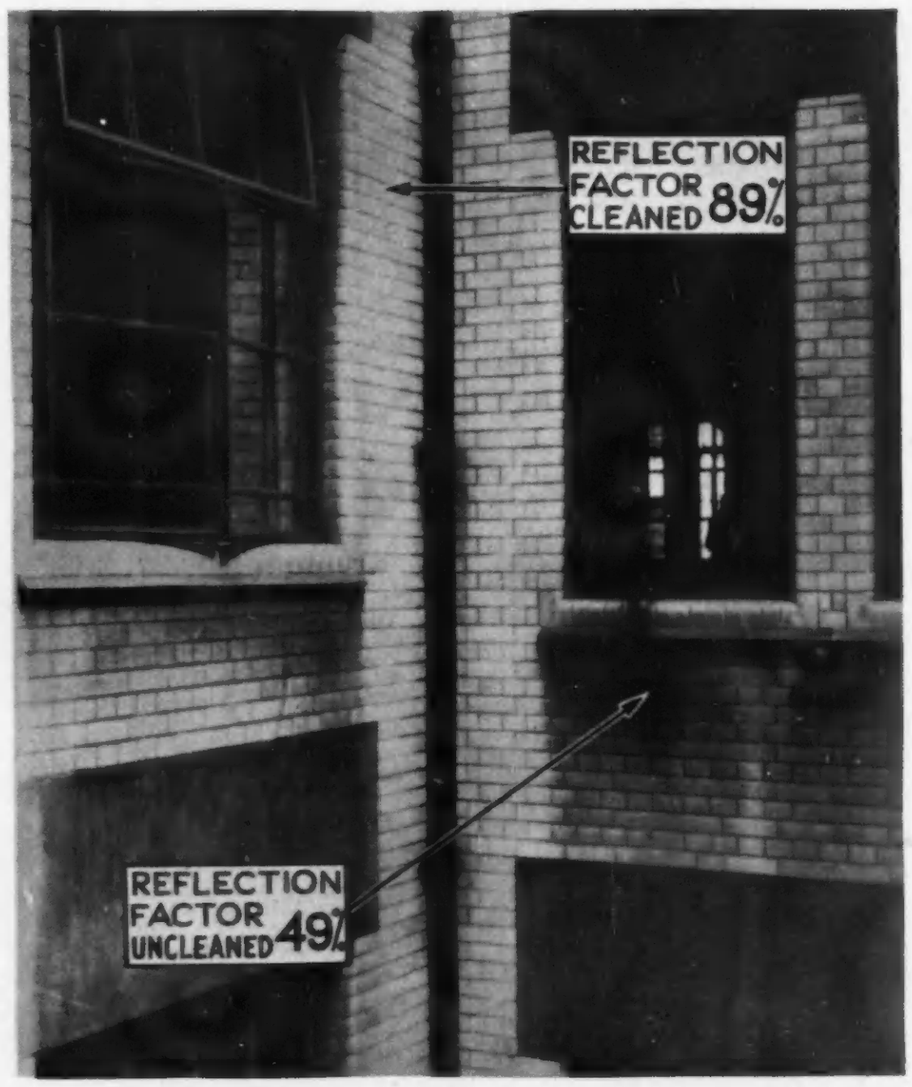

Fig. 8.—After only one year's service the reflection factor of a well having white glazed bricks can fall to about half its original value.

experienced towards the close of winter afternoons, but also during particularly dull and cheerless days, has proved so beneficent a factor in the well-being of the occupants of the rooms containing windows looking into the well, and results in so noticeable an increase in their working efficiency, that its cost is more than justified. The practice is, therefore growing in popularity, and the provision, in new buildings, of floodlighting equipment for this purpose is now looked upon as a matter of course. The illumination, to a sufficiently even degree, of the large and lofty vertical surfaces encountered is not by any means as easy as might be supposed. The equipment, if it is to prove both effective and economical, must be specially designed for the purpose, and as the over-all efficiency of such an installation is directly dependent upon the condition of the walls, the maintenance of sufficiently clean surfaces is of the greatest importance.

Although not singled out for attention by the critics, the natural phenomenon known in archi-

tectural circles as "selective discolouration" is germane to the condition of surfaces and at this stage may conveniently be considered in its relation to floodlighting. "Selective discolouration" is the term by which is designated the peculiar effect of weathering whereby, for reasons which are at present obscure, adjacent blocks of stone, or even adjacent portions of the same block, appear either dense black or almost pure white. Examples

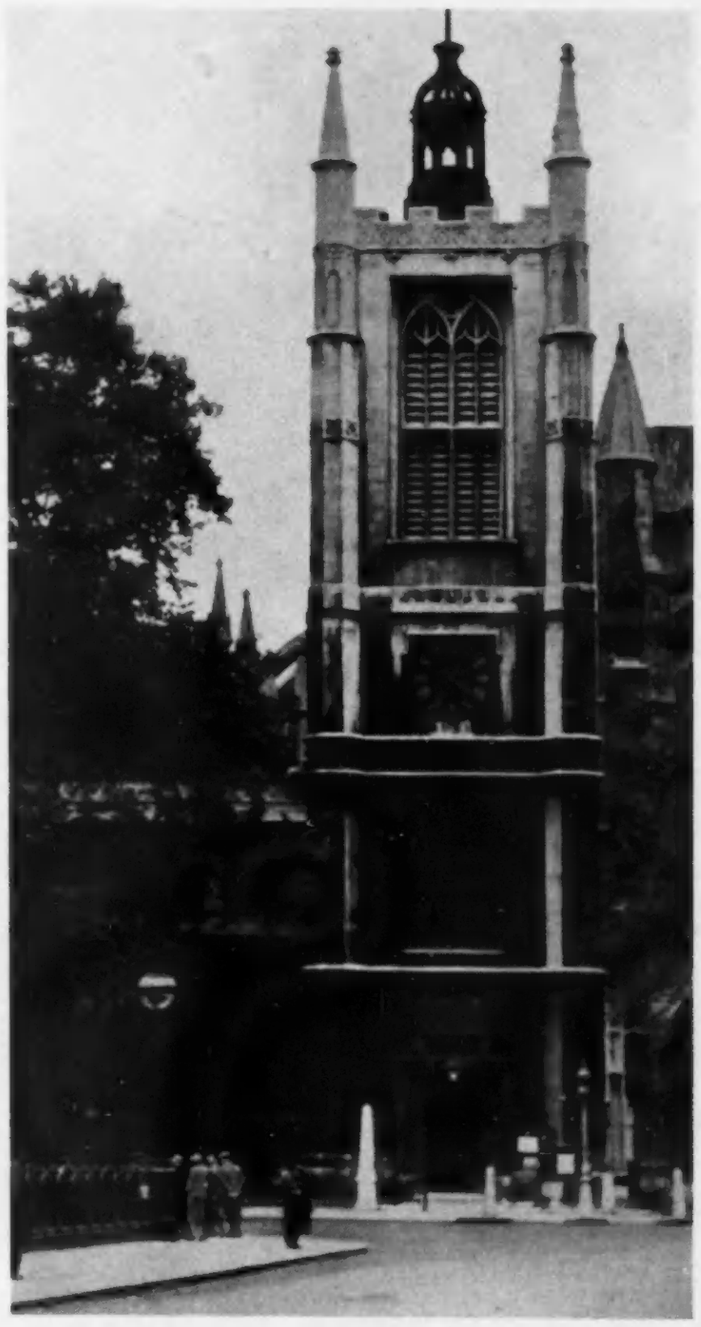

Fig. 9.—St. Margaret's, Westminster, built of Portland stone.

are to be found in buildings of sufficient antiquity in any large city, more especially should they happen to be built of Portland stone such as the Bank, the Royal Exchange, the Mansion House, St. Paul's Cathedral, the Law Courts, the British Museum and all the Wren churches. Many people are quite unaware of the fact that Portland stone is not white until it has been weathered, but that this is so can be proved by comparing the new Bush House with ancient Somerset House. If left undisturbed for a sufficient length of time, Bush House "will lose its look of sunburn and gradually grey down to the silver monotone of London."

Typical examples of the effect produced by this means are shown in the photograph of St. Margarets', Westminster, reproduced in fig. 9, in that of the interesting old Watch House, dating from 1791, reproduced in fig. 10, and in that of the group of statuary surmounting the entrance to the Old Bailey, which is shown in fig. 11. The difficulty with which the illuminating engineer has to cope is that of the excessive contrast which is introduced. As instancing the order of variation which may be encountered, the reflection factor of the blocks of stone forming the left-hand pillar of the gateway shown in fig. 12 ranges from 6 to 73 per cent. That is to say, the lightest portions are more than twelve times as bright as the darkest.

As in photography it is essential to expose for the shadows, which otherwise appear on the ultimate print as silhouettes, so in flood-lighting the intensity provided should always be sufficient to illuminate the darker portions of the subject to a level at which reasonable detail becomes clearly visible. This could easily be arranged were it not for the fact that, if an unpleasant "soot" and "whitewash" effect is to be avoided, particular care must at the same time be taken not to over emphasise the brighter portions. It is, therefore, fortunate that, as is shown by fig. 9, and even more clearly by fig. 13, the upper portion of the buildings exhibiting this effect of selective discolouration are usually very much lighter than the

Fig. 10.—The Old Watch House, St. Bartholomew's Priory, built in 1791 of Portland stone.

lower. As in the majority of cases it is necessary to floodlight from below, a compensating factor is automatically introduced, as from floodlights located in this position the intensity on the upper portions naturally falls off owing to their greater distance from the projectors and the more acute angle at

which the light rays strike the surface. If the floodlights are fixed at higher levels, the desired effect must be obtained by so training them that

Fig. 11.—Effect of "selective discolouration" on the group of statuary surmounting the entrance to the Old Bailey.

Fig. 12.—The "reflection factor" of the blocks of Portland stone forming this gateway varies between 6 and 73 per cent.

Fig. 13.—The upper portion of old buildings built of Portland stone are generally much lighter than the lower.

the total light flux is correctly apportioned between the light and dark portions.

(*d*) "*Fenestration is ignored.*" Fenestration—defined as "the series or arrangement of windows in a building"—is of the greatest importance in the creation of an effective, vigorous and pleasing facade. Not only the number, size, shape and location of the actual windows, but also the proportion of plain spaces to windows, the depth of reveals, and even the patterning of the window bars play their part, and the feelings of an architect who, after devoting

much thought and care to these details, sees them submerged and "flattened out" by floodlighting of the type which provides little beyond a crude inundation of raw non-directional lighting can more readily be imagined than described.

Unhappily, fenestration is ignored in far too many cases, but in justice to the illuminating engineer it must be stated that the responsibility for its neglect rarely rests wholly upon his shoulders. Its effective treatment usually involves the provision of an appropriate scheme of general illumination upon which is superimposed an individual and sectional scheme designed specially for each building in such manner as to disclose the distinctive features of each and to give true relative value to both fenestration and design. Such an installation involves not only a

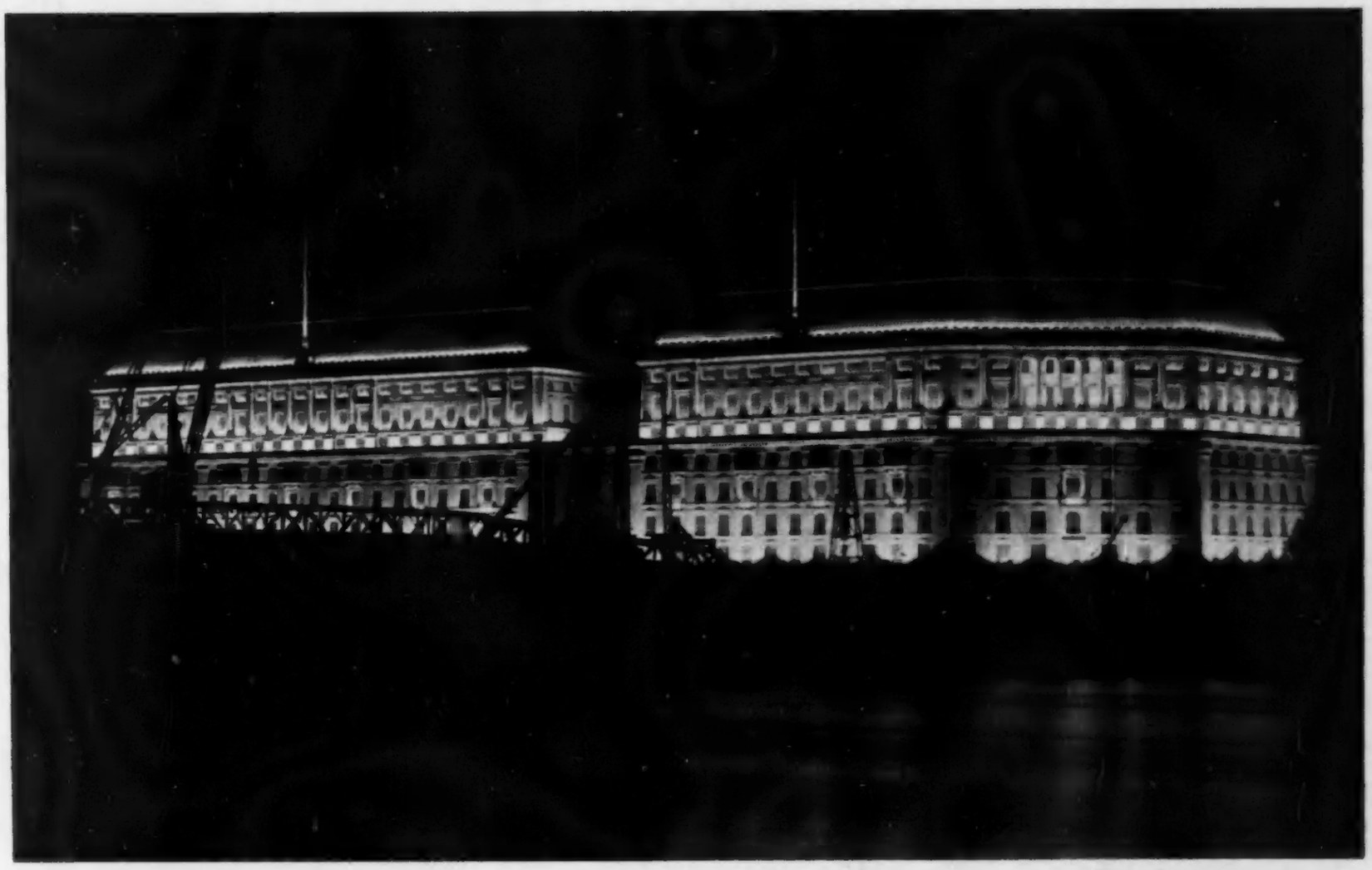

Fig. 14.—Thames House, Millbank, considered to be one of the finest examples of floodlighting, and the first instance in which the roof and skyline received proper attention.

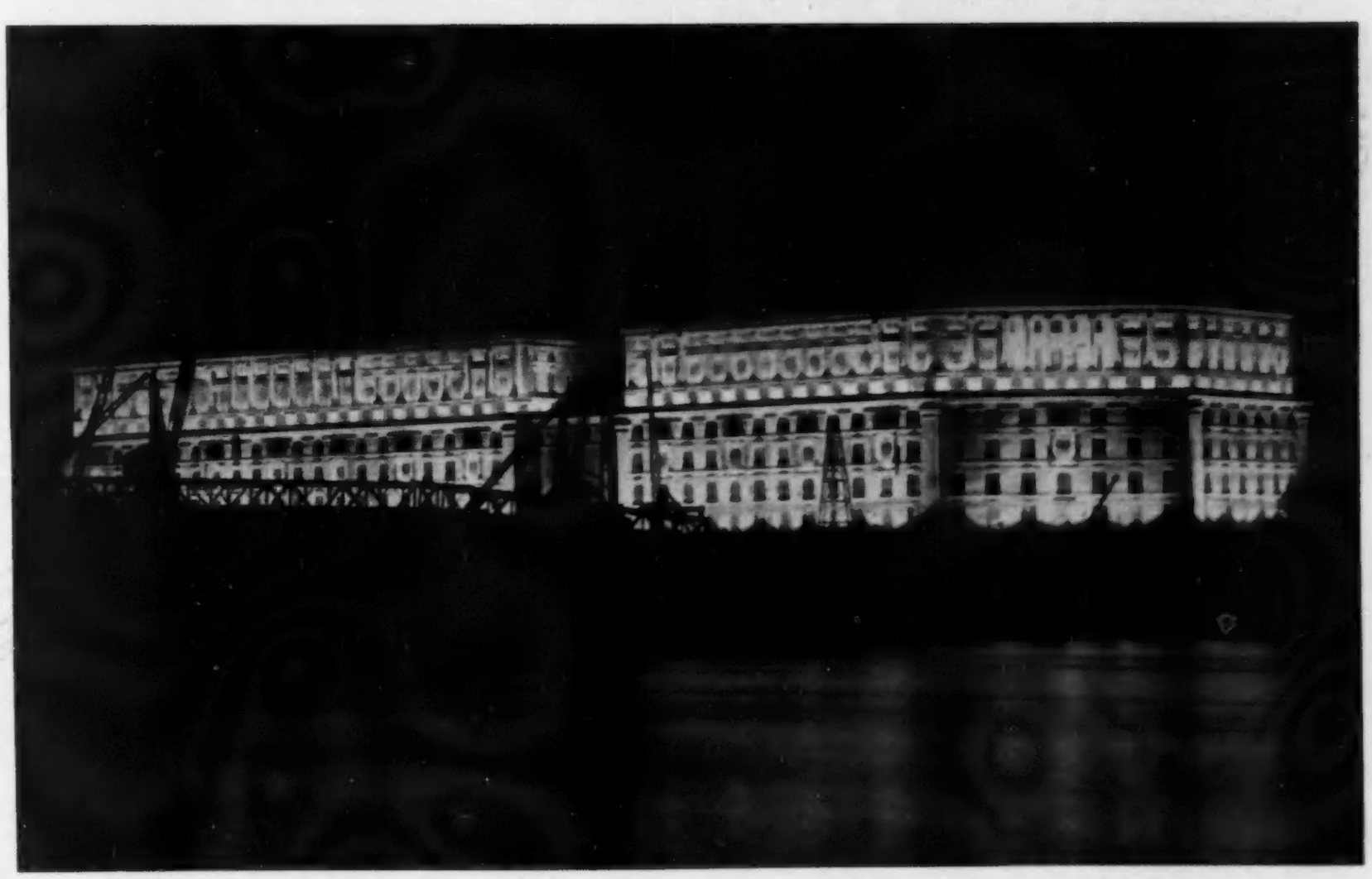

Fig. 15.—By neglecting the roof and skyline the same building shown in fig. 14 appears dwarfed and incomplete.

greater initial outlay, owing to the fact that a considerable number of individual projectors, differing in size, shape and wattage from those normally used for general lighting, must necessarily be employed, but also, and this is even more essential, a sympathetic co-operation between architect, owner and illuminating engineer. With such co-operation, the desired effect can readily be secured, as will be apparent from the photograph showing the floodlighting of Thames House, Millbank, which is reproduced in fig. 14. This installation was considered by many the most beautiful and most distinctive of the floodlighted buildings of London. It was designed in its entirety by Sir Frank Baines, the architect responsible for the building, who, in addition to drawing up the scheme, supervised its execution. His scheme provided not only a pleasing general illumination, but the throwing up of every architectural distinction. The revealing of the proportion of the plain spaces to windows, the depth of the reveals, the "features" of the facade, the patterning of the window bars, the roof, the skyline and even the flag-staffs received individual attention, and the result provided a most successful demonstration of the value of close and enthusiastic co-operation between the architect and the illuminating engineers.

(*e*) "*Roofs are neglected, with the result that buildings appear unfinished.*" This is both a pertinent and a perfectly just criticism. Roofs have been almost entirely ignored in such floodlighting as has been carried out in the past, and it is believed that the installation illustrated in fig. 14 is the first in which the illumination not only of the roof as a whole, but also of the actual skyline has received deliberate attention. The point is one which probably could only have been perceived and appreciated at its true value by an experienced architect, and the fact that so helpful and constructive a criticism should have been levelled, is evidence of the increased interest which is now being taken in floodlighting by the architectural profession. The illumination of the roof of the building illustrated in fig. 14 is effected by the use of a continuous line of trough reflector, constructed in sections, and of a contour specially designed to project a soft and carefully graduated glow of light over the flat slope of the roof, and in particular, to illuminate the top of the ridge tiles along the sky-line to a higher intensity than that of the adjacent roof surface. The soundness of the criticism, and the surprising extent to which the appearance of a building is altered by the omission of the roof surface and the sky-line

Fig. 16.—The floodlighting of the Fitzwilliam Museum, Cambridge, called for more than ordinary care.

will be apparent from fig. 15. This shows the building illustrated in fig. 14 minus the roof, and therefore, as it would have appeared, by night, and with the floodlighting in operation, had the lighting of the upper portions been neglected. The dwarfing of the facade, and the apparently incomplete and, unfinished appearance of the building as a whole, immediately arrests attention, and, with so outstanding an example of the advantage secured by such treatment, there is little doubt that the future will witness a considerable extension of its adoption.

(*f*) "*The sense of depth is lost.*" That this may be true, and that the sense of depth may be destroyed, has already been made clear by the photograph reproduced as example (F) in fig. 2. That it *is* true in many cases is regretfully admitted, but that it *need* ever be true cannot for one moment be conceded. The extent to which receding planes are caused by unsuitable floodlighting, to appear as one, is a direct measure of the inability of the designer of the installation to cope with the problem he has attempted to solve. Given a sufficiently skilful and experienced designer, supported by a sufficiently comprehensive range of equipment from which he can choose, there is not the slightest necessity for failure in so fundamental and vital a matter, and if, therefore, this defect is evident to an appreciable extent the installation should be rejected without question. The proof of this argument is well illustrated in the following example.

The floodlighting of the exterior of the Fitzwilliam Museum, at Cambridge, justly famous for the purely classical character of its design, needed more than ordinary care. The appearance of the wonderfully beautiful octastyle Corinthian portico, which constitutes the principal feature of the facade, could easily have been ruined by unsuitable, or unsympathetic treatment, and the museum authorities, realizing their responsibility, were at the outset more than doubtful as to whether an entirely satisfactory method of floodlighting could be evolved. It is, therefore, gratifying to record that an inspection of the ultimate result of the work carried out by the G.E.C. completely dispelled whatever doubts they may have had. The concensus of opinion was that, not only had the illumination closely approached the ideal, but that it disclosed features of interest, and beauty of detail, which had for long remained unknown and unsuspected, for the simple reason that never had they been revealed by the light of day.

Examination of fig. 16 discloses no less than four receding planes which really do recede. The supporting columns, although deliberately illuminated to a lower level than that of the surface against which they are viewed, are sufficiently lighted to make manifest the fact that they are columns and not flat strips. Not only can the individual stones of which they are formed be seen, but even the discolouration upon their surface is visible in the reproduction, from which it is also apparent that it is possible to walk behind the pillars. The fluted pilasters flanking the doorway on the inside wall are obviously fluted, and are equally obviously raised from their background. The ornately carved capitals, and the mouldings on the rear wall are full of light and shade, whilst the niche on the right-hand front wall presents quite palpably the appearance of a recess. The mouldings surrounding the triangular pediment appear in their natural boldness. The figures in the tympanum not only stand out in relief, but retain roundness and a definite sense of form,

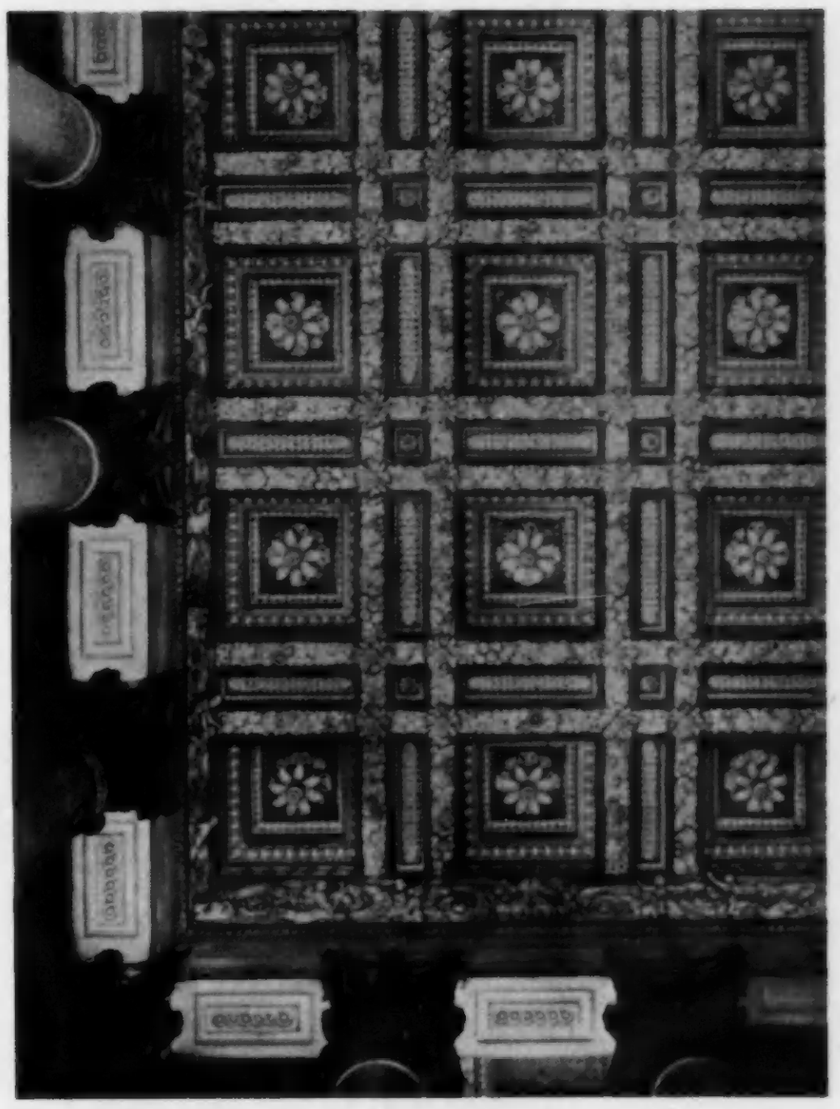

Fig. 17.—Part of the coffered ceiling of the Portico of the Fitzwilliam Museum; it will be seen that the sense of depth is retained by correct floodlighting.

and even the critics could not, with any degree of truth, complain of loss of depth. On the contrary, it has been stated by those skilled in the technicalities of art and architecture, that the illumination of this particular edifice was a remarkable example of co-operation of conception and execution.

In fig. 17 is reproduced a photograph of a portion of the coffered ceiling of the portico. Here again, although the photograph was taken under difficulties, the sense of depth is almost perfectly retained. Little or nothing of the wealth of detail rendered visible by the artificial lighting can be seen by daylight.

Other more recent, and certainly not less beautiful examples of the extent to which the sense of depth

and distance may be retained by the skilful application of a suitable combination of general and directional floodlighting are afforded by the strikingly beautiful photograph reproduced in fig. 18, showing the Doric colonnade of the Parthenon as it now appears during the hours of darkness. Few of us realize, as we should, that the perfection of classical architecture is attributable in no small measure to the sense of rhythm, proportion and suggested progression imparted by the subtle use, by those responsible for their conception, of high lights, shadows, and gradation of shade. These are provided by day by the brilliant unidirectional rays of the sun and the softly diffused light of the sky and it is indeed high tribute to the perfection attained by modern floodlighting that its services should have been utilized for the strengthening of the appeal of such "sermons in stones."

Fig. 18.—The strikingly beautiful effect obtained by floodlighting the Doric colonnade of the Parthenon.

Electric Thermal Storage Cookers.

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and
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IT is not usually realised that storage cooking, using the term in its widest sense, is by no means a modern development. The earliest use of the system was probably that made by the primitive races who kindled a fire, allowed it to burn out, and then cooked their food by burying it in the hot ashes. Later the principle was applied to wood- and coal-fired ovens for the baking of bread and other purposes. These ovens, many of which are still in regular use in country districts, are constructed either of brick or stone, and the fire is lighted inside the oven itself and allowed to burn until the fabric of the oven has become thoroughly heated. The fire is then raked out and replaced by the food, which is cooked entirely by the heat stored in the oven walls.

These older applications of storage cooking originated in the difficulty which was experienced in applying the heat direct to the food. The development of properly designed coal ranges and later gas, oil, and electric cookers, overcame this difficulty and, in addition, enabled the cooking operations to be carried out more conveniently and efficiently and under better control.

THE ELECTRIC STORAGE COOKER.

In spite of the very marked increase in the efficiency of storage cooking, brought about by the application of present day scientific knowledge to cooker design, this system still inevitably calls for the consumption of a considerably greater quantity of heat energy than is required for performing the same operations by more direct means, and it may therefore appear surprising, in view of the present day demand for ever increasing efficiency, that the system should have been revived. The explanation is that, while with the older sources of heat energy thermal efficiency and financial economy are in general very closely associated, with electricity this is frequently not the case. Coal, oil or gas can be produced at a uniform rate and stored ready for use as required and the plant has consequently only to be capable of supplying the average demand. Electricity, on the other hand, cannot usually be stored and therefore the size of generating plant is determined not by the average but by the maximum demand. The load factor of a supply station, *i.e.*, the ratio of the average demand to the maximum demand, is seldom more, and frequently considerably less, than 30 per cent. It follows that most stations could increase their output by more than 200 per cent without additional capital expenditure, provided the new demand were so distributed over the day that the maximum output was not increased. As capital charges normally represent a high proportion of the selling price of electricity, it is clear that any new loads which are clear of the peak period can be economically supplied at a considerably reduced tariff. Conversely, any heavy short period demand occurring mainly during the peak period calls for an abnormally heavy capital expenditure, and such loads are not encouraged, and indeed frequently cannot be met by the supply authorities.

This state of affairs has had a very marked effect on the development of various uses of electricity, for if, as frequently happens, an operation can be performed in two ways, one of which requires a heavy consumption of energy for a short period while the second takes energy at a lower rate for a longer period, the second method, although its thermal efficiency may be lower, may be far more economical. Two good examples of this are to be found in (1) the thermal storage system of heating buildings, in which the energy is supplied entirely in off-peak periods, and (2) the well-known storage heaters for providing water for domestic purposes. In both of these cases the advantage, from the economic point of view, of the storage over the direct method is very apparent, and furthermore the storage principle is easily applied, since the heat is stored in the medium in which it is finally required and, as the temperature involved is relatively low, the storage tank can be effectively lagged at a reasonable cost.

In the case of cookers, the position is rather more complicated. The heat is required at a much higher temperature than in the case of water heaters, and the amount of lagging which can be used is limited by considerations of cost, dimensions, etc.; consequently the efficiency of the storage cooker is inevitably considerably lower than that of the conventional type. In addition, the extent to which ordinary cookers contribute to the peak demand varies between very wide limits in different districts.

Which type of cooker will be the more economical in any given area can only be determined by a consideration of their respective energy consumptions and the local supply conditions. The former point is obviously very important and as it is dependent on the particular type of storage cooker used, the discussion of this matter is postponed to a later stage in the article.

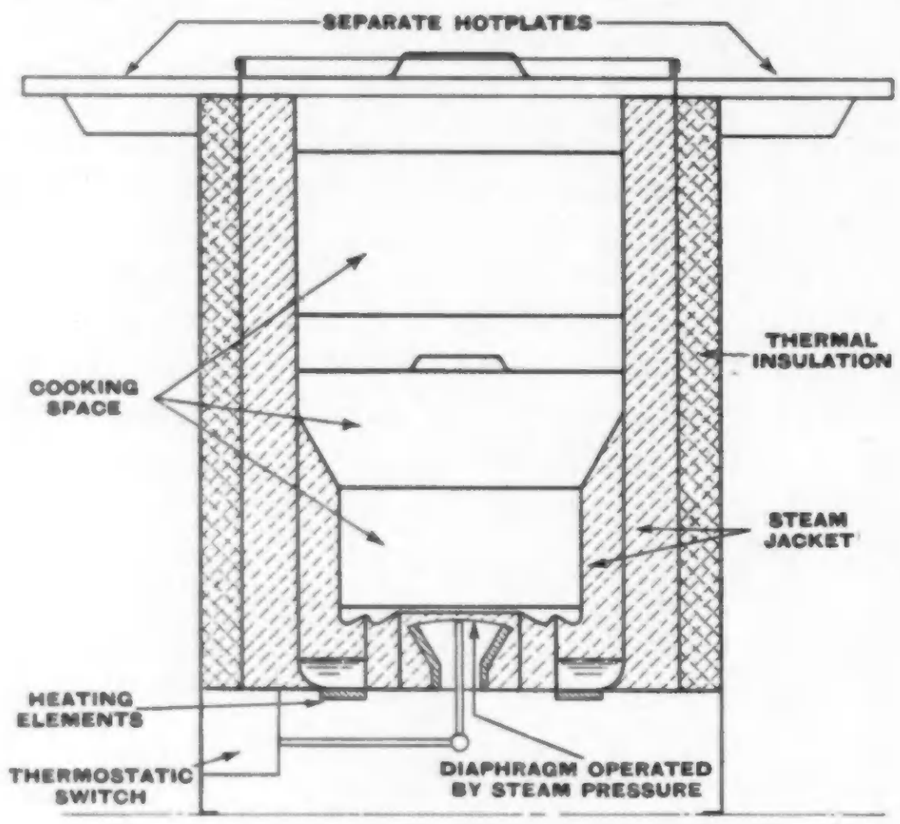


Fig. 1.—An American "fireless cooker."

GENERAL PRINCIPLES OF DESIGN.

Before considering the history of the development of electric storage cookers it will be useful to outline the fundamental requirements which have to be met in cookers of this type. Broadly speaking the essential features of a storage cooker are as follows :—

1. A heat storage medium.
2. Means of heating this medium.
3. An oven and hotplates.
4. Means of transferring the heat from the storage medium to the oven and hotplates.
5. Effective heat insulation for all parts of the cooker which are permanently hot, and a design which reduces to a minimum the conduction of heat from the storage medium to the outside case of the cooker.

While cooking operations are in progress, heat is extracted at a much greater rate than that at which it is supplied. Since there is a definite minimum temperature at which the heat is usable for cooking purposes, the initial temperature of the storage medium must be such that this minimum is never underpassed while cooking is in progress. This is a consideration which seriously limits the choice of materials. Among those which have been used or proposed are blocks of cast iron, sand, and certain liquids. The means of transferring the heat is dependent to some extent on the nature of the storage medium. If this be a liquid it may be caused to circulate through pipe coils in the oven, and through specially constructed hotplates, or, if it be a solid, the transfer may be effected by blowing air over it, or through channels in it, and circulating the heated air. Both these methods necessitate the use of a pump or fan, a feature which adds both to the initial cost of the cooker and to the cost of maintenance, and one which it is highly desirable to avoid if at all possible. A third possible method, and the one which has been adopted in the Magnet storage cooker, is to transfer the heat direct from the storage medium to boiling utensils and oven, making use of conduction in the former case and radiation in the latter.

SOME TYPICAL FORMS OF STORAGE COOKER.

An examination of the Patent Office records shows that during the past twenty years or so a great deal of consideration has been given to the design of storage cookers and much ingenuity has been expended in this direction.

Until quite recently, however, all attempts to introduce storage cookers into this country have failed, although they have for some years been fairly extensively used in certain continental countries and in America.

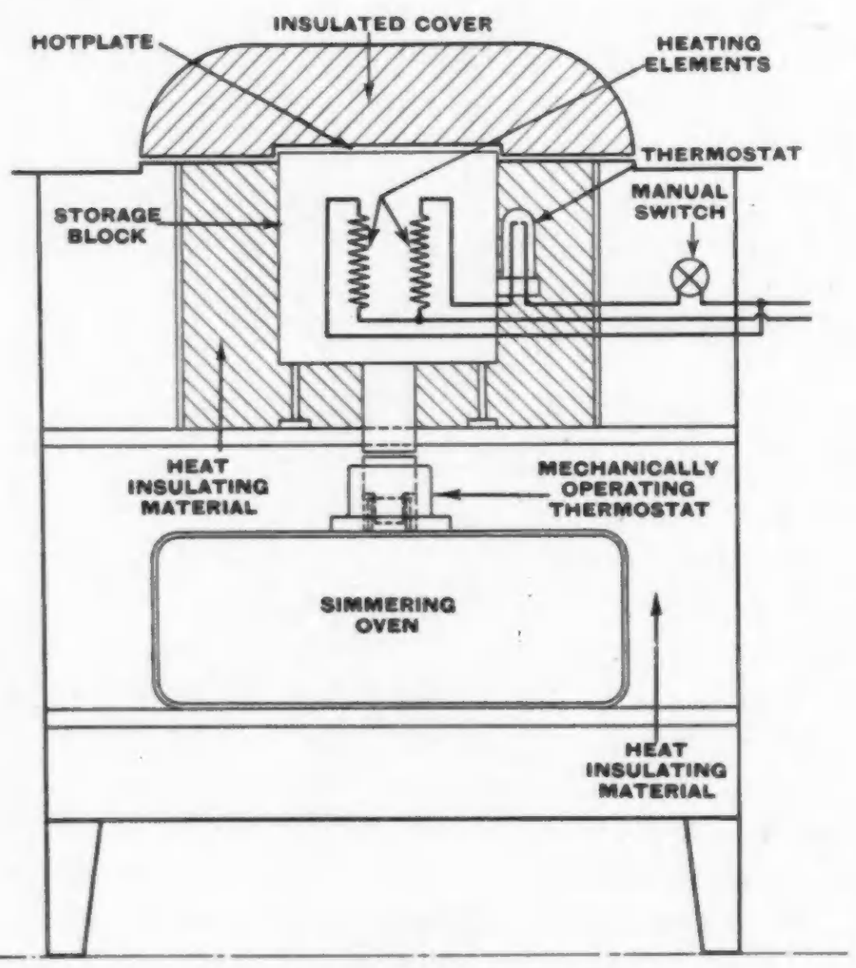


Fig. 2.—A Swedish thermal storage cooker.

The following brief descriptions of some of the storage cookers which have been used abroad are given by way of illustrating the various lines on which it is possible for such cookers to be constructed. In some cases all cooking operations are carried out by means of stored heat while in others the cookers operate only partially on the storage principle.

(a) AN AMERICAN THERMAL STORAGE COOKER.

The first type to be considered (fig. 1) is one which has been largely used in America, where it is known as the "fireless cooker." In one example the food is cooked in a vertical cylindrical chamber surrounded by a steam jacket. The water container, a boiler, is situated below the cooking chamber, the heating being carried out by thermostatically controlled elements loaded to about 550 watts. The pressure is normally maintained at about 15 lbs. per square inch (gauge). Two conventional type hotplates are provided at the side of the cooker. No provision is made for cooking operations requiring a high oven temperature. An attempt to improve on this type of electric cooker, was made* several years ago, by substituting cast iron for water as the storage medium. In the modified cooker, heat is stored in a number of cast iron discs which are normally contained in a special storage chamber provided with a heating element loaded to about 200 watts. The storage chamber has a heat-insulating lid, and above this the cooking chamber is situated. This also is provided with a heat-insulating lid and the whole cooker is well lagged. The cooker is surrounded by a water container. The cooking chamber is heated by transferring to it one or more discs, the number required depending on the amount of food which is to be cooked. An A.C. electromagnet is used for raising the lid of the storage chamber and the heated cast iron discs. For broiling, frying, etc., a separate radiant grill loaded to 700 watts is provided, and the switching is arranged so that when this separate grill is in use the storage element is out of circuit.

* Elec. Review (London) 1915, p. 199.

(b) A SWEDISH THERMAL STORAGE COOKER.

A cooker which is widely used in Sweden is illustrated diagrammatically in fig. 2.

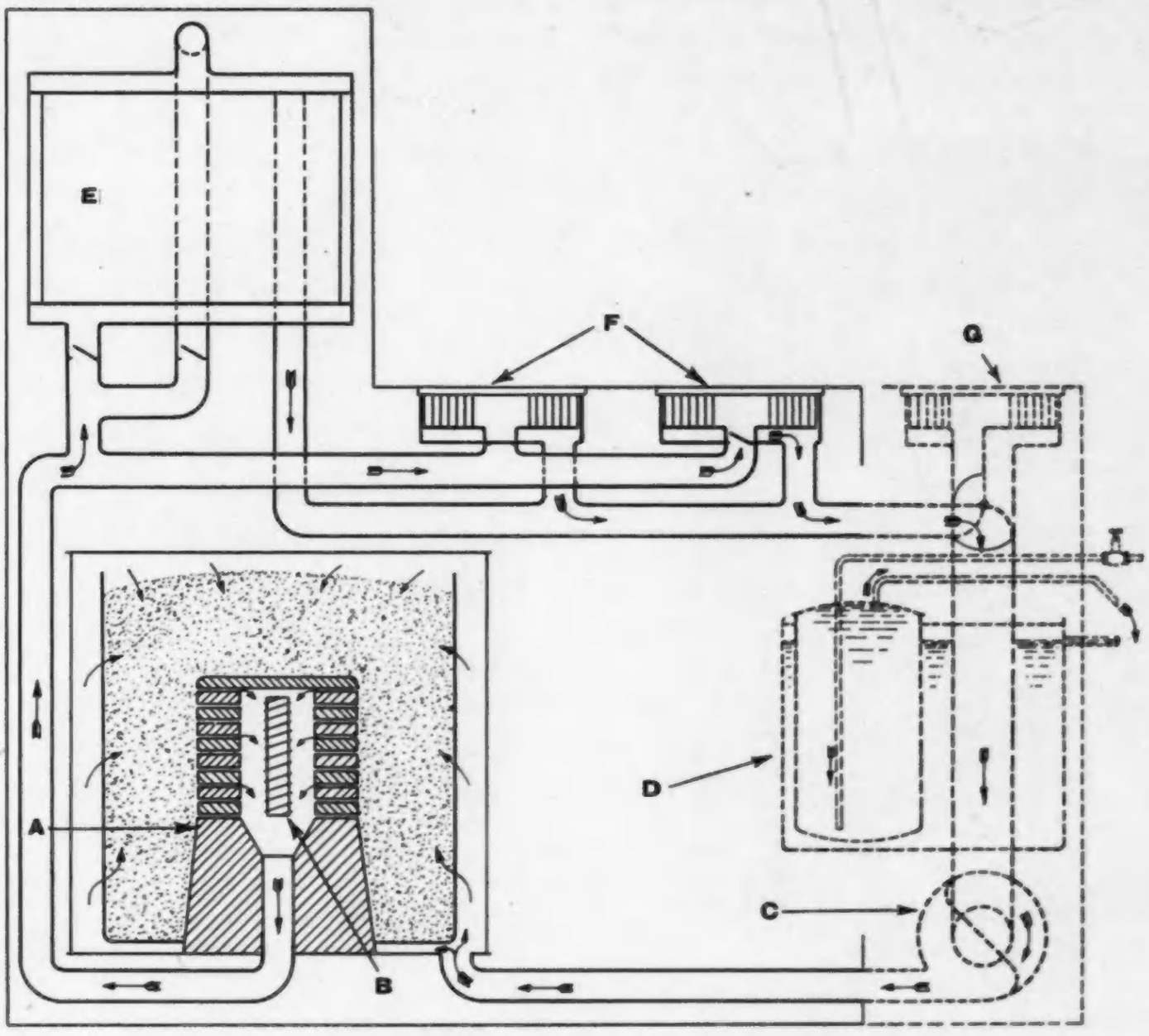


Fig. 3.—A Swiss thermal storage range.

This cooker employs as the storage medium a cast iron block which is heated by two separate elements, loaded to about 350 watts each. One element is connected permanently in circuit, while the other is thermostatically controlled and comes into use when the temperature of the block falls below 900°F. In addition, this second heating element may be switched off manually when the amount of cooking required is very small. The top of the storage block is machined flat and serves as a hotplate, while its lower face transmits heat to a simmering oven by means of a metallic conducting path which can be interrupted thermostatically. This arrangement maintains the temperature of the oven at about 195°F. Foods such as vegetables, boiled meats and fish, puddings, etc., which are normally cooked by simmering on a hotplate, are

first boiled upon the hotplate in the usual way and then placed in the simmering oven for a relatively long period, depending on the nature of the food being cooked. A separate roasting and baking oven of conventional type is provided, and when this is in use the energy is diverted from the storage apparatus in order to minimise the power demand on the supply system.

(c) A SWISS STORAGE COOKER.

In the last mentioned cooker, roasting could only be carried out by the use of a separate oven of standard type. A cooker which enables all normal cooking operations (except grilling) to be carried out

Fig. 4.—The Magnet electric thermal storage cooker ; views show closed and open positions.

by means of stored heat is produced in Switzerland. A diagrammatic sketch of the range is given in fig. 3. The heat is stored in a cast iron block A, surrounded by sand, which is heated by a heating element B, the loading of which can be adjusted to suit the average cooking requirements. Heat is transmitted to the various cooking points by means of air circulation. A small fan C, taking about 60 watts, forces the air through the storage unit, from the outer surface towards the centre, and then to the oven, E, and the two main hotplates, F, the flow being controlled by means of valves. On leaving these hotplates the air may be directed to a third hotplate, G, situated towards the back of the hob, which is used solely for simmering. From this simmering-plate the air passes finally to a water heater D, where the remainder of the heat is given up. If the simmering-plate is not in use, the air passes directly to the water-heater from either of the main hotplates or the oven.

A thermal-switch is incorporated in the construction of the range, and disconnects the supply in the event of the range being left idle for a considerable period. The supply is automatically switched on again when the temperature of the storage unit has fallen to a definite value. The total weight of the complete range is about 7 cwts.

(d) AN ITALIAN STORAGE COOKER.

Several storage cookers have been developed to suit the conditions existing in Northern Italy. In this region electrical energy is generated chiefly from a plentiful supply of water-power, and the conditions are therefore particularly adapted to thermal storage methods.

In one particular make of these cookers (which may be taken as typical) the loading is constant at 400 watts. The cooker is provided with two storage units in the form of cast iron blocks, provided with heating elements embedded in fireclay formers which slip into recesses in the blocks. A small oven which

would not be large enough for English methods of cooking, is situated beneath each block. These ovens are maintained at a suitable temperature for the usual roasting and baking operations by means of heat leakage from the storage blocks through suitable insulating material. A water heater is incorporated, the container of which is situated outside, and around, the thermal insulation of the cooker. By this means the total thermal losses from the combined arrangement are reduced to a very low value, but the combination necessarily becomes rather bulky.

A number of electric storage cookers similar to that described above were tested out in this country, about 10 years ago* but there is no record of them having been installed on any appreciable scale. This was probably largely due to the general unsuitability of the design to English conditions. It is interesting to observe, however, that the advantages of the thermal storage system of electric cooking were appreciated by Supply Engineers so long ago.

(e) A NORWEGIAN SEMI-STORAGE COOKER.

In addition to the above, certain cookers are used in Norway which can best be described as semi-storage cookers. A storage block is used as the rapid boiling plate and for heating the oven, while low loaded hotplates with independent elements are used for simmering purposes.

THE MAGNET STORAGE COOKER.

All of the cookers which have so far been described were developed to meet the particular conditions obtaining in their countries of origin. The methods on which English cooking is based, although of widespread use in many parts of the world, do differ sufficiently from those in use in certain parts of the Continent to call for rather different equipment. The Magnet storage cooker, which is described below, has been developed by the G.E.C. with the special aim of making its application as widespread as possible.

The external appearance of the Magnet storage cooker is shown in fig. 4, and it will be noticed that the general lines are very similar to those of the conventional type of cooker. The construction is illustrated diagrammatically in fig. 5.

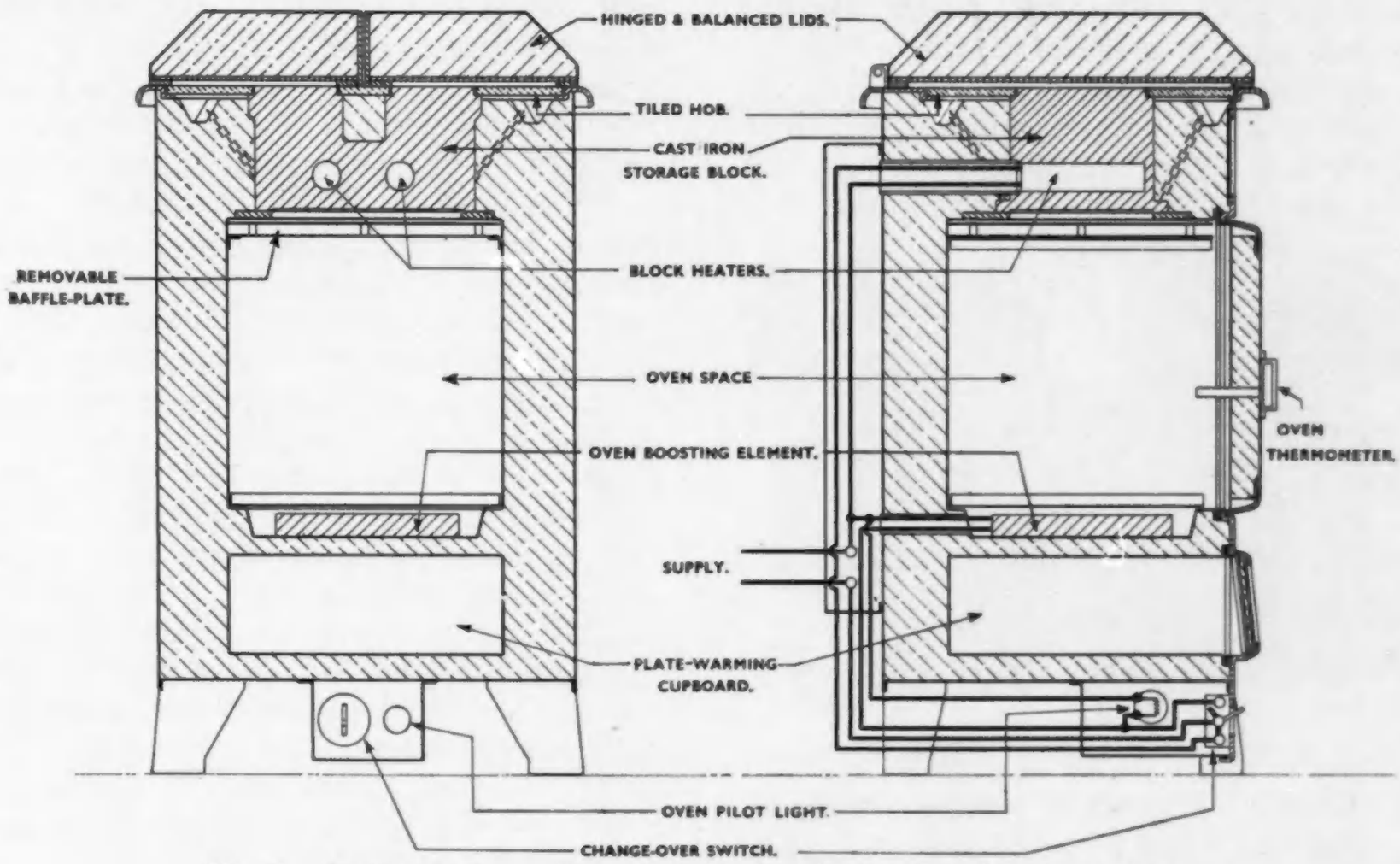


Fig. 5.—Sectional views of the Magnet electric thermal storage cooker.

The storage medium, a block of cast iron weighing about 130 lbs. (fig. 6) is heated by means of two embedded type heating elements, having a combined loading of 500 watts, which are fitted in recesses provided in the block.

Special attention has been paid to the method of mounting the block in the cooker in order to reduce to a minimum the amount of heat conducted from the block to the external case and for the same reason the hob is made up of glazed porcelain tiles, fitted between the hotplates and the vitreous enamelled surround. The space surrounding the storage block and oven is filled with slag-wool, the thickness of which is about 4in. all round the oven and 6in. round the sides of the block. The upper portion of the block is split into two parts, the upper surfaces of which are machined flat and serve as hotplates. Each hotplate is provided with a well lagged hinged and balanced lid, thus enabling one plate to be kept covered whilst the other is in use. Heat is transmitted to the oven by radiation, from the under

* Electrical Times (1922) p. 599.

surface of the storage block, through an aperture in the top of the oven, a removable baffle plate being provided which is placed below the block in order to minimise heat radiation when the oven is not required for use for roasting or baking purposes.

The radiation from the block is not sufficient to raise the oven to roasting temperature and a separate boosting element loaded to 500 watts is therefore provided in the bottom of the oven. The switching is arranged so that when this boosting element is in use, the block heating elements are switched off, thus maintaining the load taken by the cooker constant at 500 watts. The hotplates can, of course, be used at the same time as the oven, as, owing to the high heat capacity of the block, the fact that its heaters are switched off while the oven is in use has but little effect on its temperature. A thermometer is provided on the oven door to indicate at all times the temperature conditions inside the oven.

Fig. 6.—Block of cast iron used as storage medium.

A plate-warming cupboard is situated below the roasting-oven and receives heat by leakage through a suitably arranged layer of insulating material. At the front of the cooker, and beneath the plate-warming cupboard, is the change-over switch controlling the oven boosting element, together with an indicating lamp which shows clearly when this element is in circuit. The overall dimensions of the cooker are: 3′ 5″ high by 2′ 1″ wide by 2′ 1″ deep. The dimensions of the oven cooking space are approximately 14″ by 14″ by 14″, and the plate-warming cupboard is 4″ high by 15″ wide by 15″ deep. The hotplates both measure 7″ by 4½″.

OPERATING CONDITIONS.

So far as methods of use are concerned, the cooker differs but little from electric cookers of the conventional type. Boiling operations are carried out on the hotplates in the usual way but in a much shorter time than is possible with ordinary type cookers. When the cooker is first used in the morning and the block is at its maximum temperature, two pints of water can be boiled from cold in from 3 to 4 minutes. During the day, as the temperature of the storage block gradually falls away owing to the heat extracted during cooking operations, the boiling time increases somewhat, but even at the end of a day's cooking, when the block temperature reaches its lowest value, the boiling times do not exceed those obtained with ordinary enclosed type electric hotplates.

Grilling can be carried out with this cooker in a very satisfactory manner, provided the block is near its maximum temperature, by placing the food to be grilled at the top of the oven and exposing it to the radiation from the under side of the block; but the temperature of the block is not quite high enough to enable toast to be prepared in this way. Even with the baffle-plate in position, a small amount of heat leakage occurs from the storage block into the oven. As a result, the oven is constantly maintained at a low cooking temperature (about 300°F. to 350°F.) and is thus always available without any pre-heating for cooking operations requiring a slow oven.

When a quick oven is wanted for roasting or baking, the baffle-plate is removed and the oven boosting element switched on; the oven is then ready for use in from 10 to 20 minutes.

The cooker provides ample cooking facilities for a family of from 4 to 6 people including the provision of a hot meal at mid-day, as well as in the evening. If only one of these meals is required, the cooker will serve for a larger number of people. The cooking facilities include full use of the oven for roasting, baking cakes, etc., and use of the hot-plates for all boiling and simmering operations, including the boiling of water from cold for making tea, coffee, etc.

The only precautions which are necessary to ensure satisfactory service are that the covers over the hotplates be kept closed when the hotplates are not in use, and that flat bottomed utensils be employed for boiling purposes.

The curve in fig. 7 shows how the block temperature varies during a full day's cooking operations.

THE ECONOMICS OF STORAGE COOKING.

As has already been stated elsewhere in this article, storage cookers do not necessarily show an economic gain over cookers of the ordinary type; in fact, they should not be considered as being primarily intended to compete with such cookers. Their value lies rather in the fact that they enable electric cooking to be introduced into areas in which, for one reason or another, it is either impossible for cookers of the standard type to be used at all, or, if they can be used, the rate which has to be charged for energy is so high as to be practically prohibitive.

It is impossible to lay down any general rule as to the conditions under which storage cookers can be profitably used, as it is really necessary for every case to be considered on its merits. There are, however, certain guiding principles which should be borne in mind, and these can best be explained by taking the Magnet cooker as an example. The

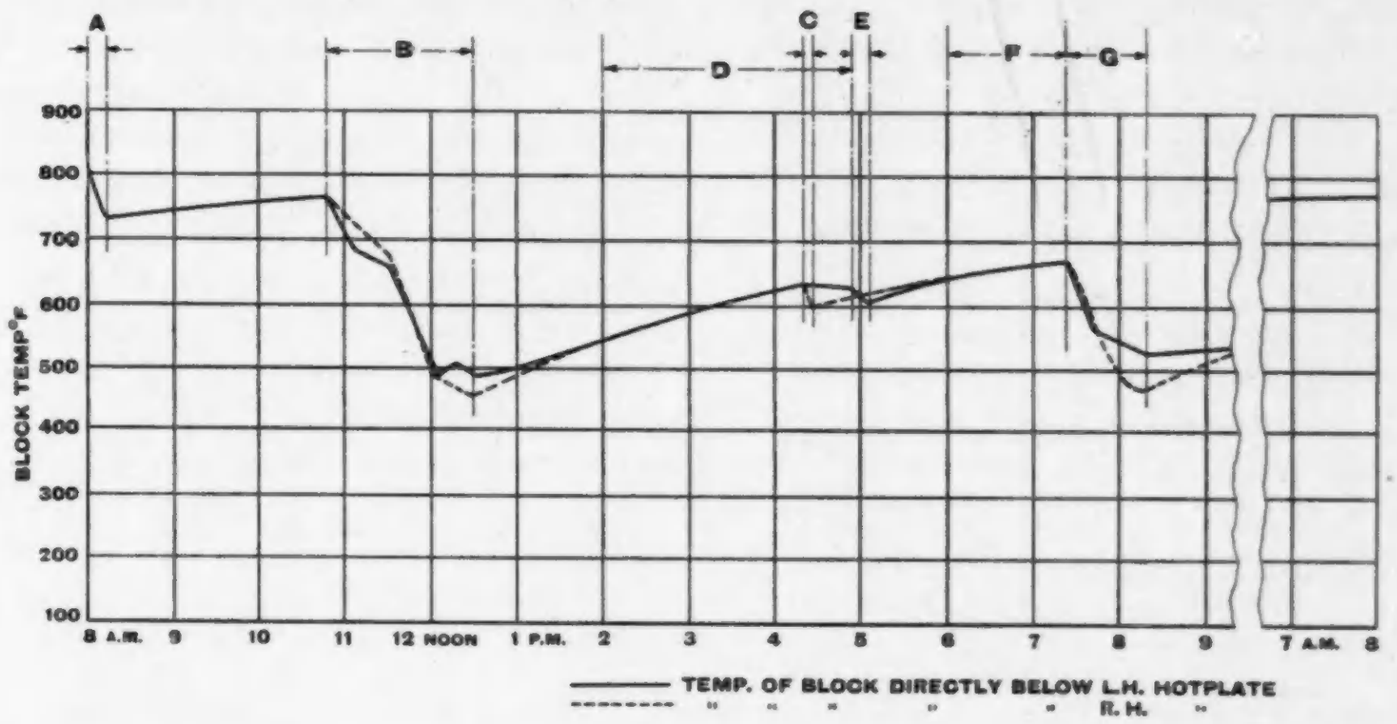
figures given and conclusions reached can readily be modified to render them applicable to other storage cookers having loadings and cooking capabilities which differ from those of the Magnet cooker.

In districts in which, on account of lack of copper or limitations in generating capacity, ordinary cookers cannot be installed, the only question is whether energy can be supplied for the storage cooker at such a price as to bring the cost within the range of the consumers concerned. What this price is, must obviously depend on the financial status of the individual consumer, but, unless the circumstances are quite special, ¾d. a unit, at which price the annual charge for energy will be £13 13s. 9d. should probably be regarded as an upper limit, while, with working class consumers, the tariff should certainly not be more than ½d. per unit, which gives an annual charge of £9 2s. 6d.

In districts in which standard type cookers can be used, it is necessary for the Supply Authority to determine if it will be to its advantage to quote such terms for the use of the storage cooker that the total cost to the consumer will be no greater than it would be for a standard type cooker giving the same service. It is probable that the most usual practice will be for storage cookers to be supplied at an inclusve annual charge including energy, rental, maintenance, and in some cases installation, and all these factors have therefore to be taken into account in making the comparison. The biggest item is obviously the cost of supplying energy and this cost is made up of two parts, viz. :

1. Cost of generation or price for bulk supply.
2. Cost of distribution (including transformation).

The unity load factor of the storage cooker makes the determination of the cost under the first of these headings an easy matter. If the Supply Authority is buying energy in bulk, paying a fixed charge per annum per kilowatt maximum demand,



	Meal.	Food Prepared.	Method of Preparation.
A	Breakfast	Porridge Coffee .....2 pints Milk .....1 pint Bacon and Eggs (4)	On Hotplates. Grilled below block, in Oven.
B	Lunch	Potatoes Cauliflower Onion Sauce Custard Roast Leg of Lamb Baked Apple Dumplings	On Hotplates. In Oven.
C	Tea	Water for Tea, 2 pints	On R.H. Hotplate.
D	Dinner	Meat for Pie	Simmering in Oven, with baffle-plate in position below block, and oven boosting element off.
E	Ditto	Ditto	Simmering on L.H. Hotplate.
F	Ditto	Milk Pudding	In Oven, with baffle-plate in position below block, and oven boosting element off.
G	Ditto	Potatoes Cabbage Meat Pie Milk Pudding	On Hotplates. In Oven.

Fig. 7.—The Magnet thermal storage cooker ; curve showing variation in block temperature during a full day's cooking for six people.

plus a charge per unit consumed, the cost of energy for the storage cooker is equal to the sum of the fixed charge for one half kilowatt demand and the cost of 4,380 units. Thus, for example, if the Supply Authority is paying £3 10s. 0d. per kilowatt maximum demand and 0.25d. per unit, the cost of energy for the storage cooker (excluding distribution) will be £1 15s. 0d. plus £4 11s. 3d., *i.e.*, a total of £6 6s. 3d. per annum, which is equivalent to 0.35d. per unit. The cost of energy for ordinary electric cookers cannot be calculated with anything like the same accuracy, owing to the difficulty of determining the proportion of the maximum demand charge which should be allocated to each cooker. The average maximum demand per cooker depends, of course, on the diversity factor, being equal to the total loading of the cookers connected to the supply system divided by the product of the diversity factor and the number of cookers. Unless, however, the maximum cooker load coincides with the peak load on the supply system, the maximum demand as calculated above is not the figure required for the determination of cost.

A Supply Authority's maximum demand charge is fixed periodically on the basis of the highest value which the maximum demand reaches on any single day during that period. The information which is required to enable one to determine what maximum demand charge should be allocated to cookers is the total cooker load during the peak period on this particular day, and this load, divided by the number of cookers installed, gives the maximum demand charge which is attributable to each cooker.

In an area in which there is a considerable industrial load the highest peak will probably occur in the early evening when the industrial and lighting loads overlap. At such a time the cooker load will be low and the maximum demand charge which should be allocated to each cooker will accordingly be small. In an area in which the supply is mainly domestic and a considerable number of cookers are connected, these may themselves cause the peak demand, and in this case the highest peak, *i.e.*, the one on which charges are based, will occur on the day on which the cooker load reaches its highest value. In these circumstances the maximum demand charge per cooker will depend on diversity factor at the time that the cooking load reaches its highest value, that is to say, on the lowest diversity factor which is obtained on any day. In such an area the maximum demand charge must inevitably be high.

TABLE I.

Tariff.		Storage Cooker.	Standard Type Cookers.								
		Max. Demand ½ kVA Energy consumption - 12 Units per day.	Max. Demand 1 kVA.			Max. Demand 1½ kVA.			Max. Demand 2 kVA.		
Per kVA Max. Demand	Per Unit.		Energy consump.—units per day.			Energy consumption—units per day.			Energy consumption—units per day.		
			4	5	6	4	5	6	4	5	6
£4 0 0	.3d.	£7 9 6 .41	£5 16 6 .96	£6 5 7 .83	£6 14 9 .74	£7 16 6 1.28	£8 5 7 1.09	£8 14 9 .96	£9 16 6 1.63	£10 5 7 1.35	£10 14 9 1.18
	.25d.	£6 11 3 .36	£5 10 5 .91	£5 18 0 .78	£6 5 7 .71	£7 10 5 1.24	£7 18 0 1.04	£8 5 7 .91	£9 10 5 1.56	£9 18 0 1.30	£10 5 7 1.13
	.2d.	£5 13 0 .31	£5 4 4 .86	£5 10 5 .73	£5 16 6 .64	£7 4 4 1.19	£7 10 5 .99	£7 16 6 .86	£9 4 4 1.51	£9 10 5 1.25	£9 16 6 1.09
£3 10 0	.3d.	£7 4 6 .40	£5 6 6 .87	£5 15 7 .76	£6 4 9 .68	£7 1 6 1.16	£7 10 7 .99	£7 19 9 .88	£8 16 6 1.45	£9 5 7 1.22	£9 14 9 1.07
	.25d.	£6 6 3 .35	£5 0 5 .83	£5 8 0 .71	£5 15 7 .63	£6 15 5 1.11	£7 3 0 .94	£7 10 7 .83	£8 10 5 1.40	£8 18 0 1.17	£9 5 7 1.02
	.2d.	£5 8 0 .30	£4 14 4 .78	£5 0 5 .67	£5 6 6 .58	£6 9 4 1.06	£6 15 5 .89	£7 1 6 .78	£8 4 4 1.36	£8 10 5 1.12	£8 16 6 .97
£3 5 0	.3d.	£7 2 0 .39	£5 1 6 .83	£5 10 7 .73	£5 19 9 .66	£6 14 0 1.10	£7 3 1 .94	£7 12 3 .84	£8 6 6 1.37	£8 15 7 1.15	£9 4 9 1.01
	.25d.	£6 3 9 .34	£4 15 5 .78	£5 3 0 .68	£5 10 7 .61	£6 7 11 1.05	£6 15 6 .89	£7 3 1 .78	£8 0 5 1.32	£8 8 0 1.1	£8 15 7 .96
	2d.	£5 5 6 .29	£4 9 4 .74	£4 15 5 .63	£5 1 6 .56	£6 1 10 1.00	£6 7 11 .84	£6 14 0 .73	£7 14 4 1.27	£8 0 5 1.06	£8 6 6 .91
£3 0 0	.3d.	£6 19 6 .38	£4 16 6 .79	£5 5 7 .69	£5 14 9 .63	£6 6 6 1.04	£6 15 7 .89	£7 4 9 .79	£7 16 6 1.28	£8 5 7 1.09	£8 14 9 .96
	.25d.	£6 1 3 .33	£4 10 5 .74	£4 18 0 .64	£5 5 7 .58	£6 0 5 .91	£6 8 0 .84	£6 15 7 .74	£7 10 5 1.24	£7 18 0 1.04	£8 5 7 .91
	.2d.	£5 3 0 .28	£4 4 4 .69	£4 10 5 .69	£4 16 6 .53	£5 14 4 .94	£6 0 5 .79	£6 6 6 .69	£7 4 4 1.19	£7 10 5 .99	£7 16 6 .86

Table I shows the annual cost of energy (excluding distribution) for storage and ordinary cookers for a number of different bulk supply tariffs. The figures for the storage cooker are based on a contribution to the peak of 500 watts, while in the case of ordinary cookers, the cost has been calculated for three different values for the average contribution to the peak, and for daily energy consumptions of 4, 5 and 6 units. In addition to the annual cost of energy, the table also shows the cost per unit. Examination of this table shows that, over the range of tariffs considered, the cost of energy to the Supply Authority is, broadly speaking, less for the storage cooker than for the ordinary cooker in all cases in which the latter type contributes not less

than 1½ kW to the peak and does not consume less than 4 units a day, while the cost per unit in the case of the storage cooker is only about one third of what it is for the ordinary cooker operating under these conditions. In such cases the Supply Authority will actually make more profit per cooker by installing storage cookers rather than standard cookers to the extent of the savings under the other headings which are about to be considered. If the ordinary cooker contributes more than 1½ kW to the peak, or consumes more than 4 units a day, then the storage cooker will also show a saving under the heading of cost of energy.

The cost of voltage transformation and of distribution account for a large proportion of the total charge made to consumers for electricity supplied for domestic purposes. This cost is due in part to the capital cost of cables, sub-stations, etc., and in part to energy losses in cables and transformers. So far as capital cost is concerned, storage cookers will show a saving unless the diversity factor of the ordinary cookers on a given distribution network is so high as to bring the maximum demand per cooker on the network down to 500 watts—which is a very unlikely state of affairs. There will be a further saving under the heading of transformation losses since the use of storage cookers, by reducing the capacity of the transformers required, will also reduce the stand-by losses.

The other directions in which the storage cooker compares to advantage with standard cookers are as follows:

1. The cost of installation is very low, being no greater than that of installing an extra lighting point.

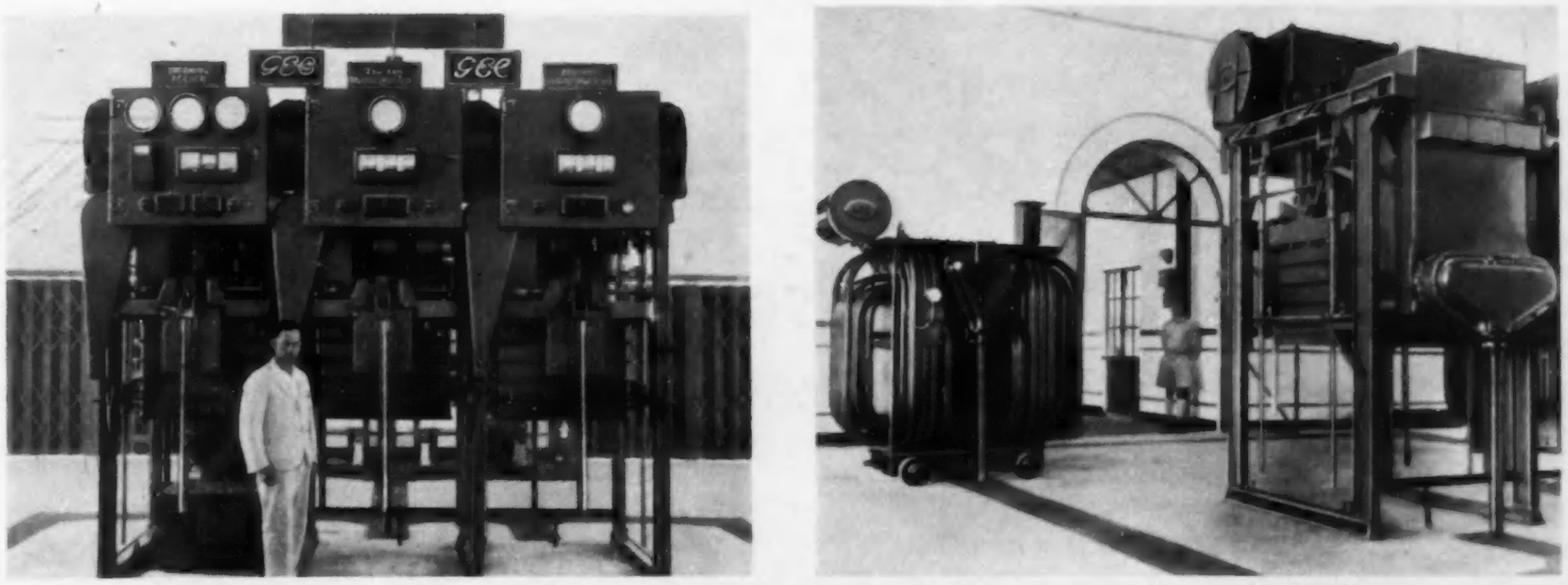
2. Cost of maintenance will be very much lower than is the case with ordinary cookers, as the electrical equipment of the cooker is limited to three heaters of very cheap form and a single 5 ampere switch.

3. Ordinary cookers are frequently installed in houses in which they receive but little use with the result that the energy consumption per cooker is very low. In any case it must be somewhat problematical. Storage cookers, however, will only be installed where they will be fully used and every cooker represents an energy consumption of 4,380 units per annum. The engineer is therefore able to work out his costs very accurately, and in fixing his tariffs, knows almost exactly what profits he will be making per cooker. Furthermore, it is probable, in view of the assured consumption of the storage cooker, that the Supply Authorities will, in general, be willing to make a lower profit per unit sold than in the case of the ordinary cooker, working rather on a basis of profits per cooker installed.

4. There is no need to meter the energy supplied for storage cookers.

A number of Supply Engineers in different parts of the country have greatly assisted in the development of the Magnet storage cooker by testing sample cookers and making criticisms and suggestions. Some 50 of the latest model have recently been installed in one area in the Midlands, mainly in the homes of working class people.

Metalclad Switchgear installed at Erode for the S.I. Railway.



Two views of the 22 kV, 350,000 kVA, 3-phase, 50 cycle, G.E.C. metalclad switchboard installed at Erode for the S.I. Railway.

The Electric Propulsion of Ships.

By CHARLES C. GARRARD, Ph.D., M.I.E.E.
Manager Switchgear and Transformer Depts. of The General Electric Co., Ltd.

The following article, which is reprinted from a paper read by the author before Section G of the British Association at York on Thursday, September 1st, 1932, gives a brief outline of the development of electric propulsion of ships, and a more detailed description of modern electric propulsion equipment.

Acknowledgment is made to "Engineering" for their kind permission to reproduce many of the illustrations.

AT first sight it might appear rather extraordinary to propel a ship by electricity. Electricity is, of course, by far the best means known for transmitting power over distances, but in a ship, the distance the power has to be transmitted is only a few score feet. To do this electrically, two transformations are necessary, that is, from mechanical to electrical, and back again from electrical to mechanical, in order to transmit the energy of the prime mover to that of the screw.

The earliest examples of electrically-propelled ships were, probably, two fire boats placed in service in Chicago in 1908. One of the earliest larger electrical vessels was the collier *Jupiter* (5,400 shaft horse-power), which dates from 1912-1913, and is still in commission with the original machinery, under the changed name of U.S. Airplane-carrier *Langley*. This ship was the forerunner of electric propulsion in the American navy.

On the basis of the known losses of the different types of propelling machinery, it is generally possible to prove mathematically that the electric system is the most efficient, the main consideration in such a calculation being the different power requirements of the screw and the prime mover. The difference in speed between the two ends of the driving equipment necessary to obtain efficiency, involve the use of some kind of gearing between them, and it is the ability of the electric drive to act as a speed changing gear, which gives it its advantages. The problem is, however, an economic one, and the effect which the electric drive has on the revenue earning capacity of the ship as a whole is probably more important than the reduction of fuel costs. In some cases, the greater amenity of electrically propelled passenger ships is of great value, and in other cases, increased ease of control and manœuvring are the determining considerations. The question of the adoption of electric propulsion for a particular vessel is, therefore, one for the naval architect rather than for the electrical engineer.

I do not propose in this paper to prove the economic advantage of the electric drive as applied to the propulsion of ships. The large number of electric ships already built—there are nearly one hundred turbo-electric ships in existence, or building, with a total horse-power of upwards of one million, and a total shaft horse-power of Diesel-electric ships exceeding 100,000—may reasonably be said to render the repetition of such proof unnecessary. The number of ships of all kinds having Diesel-electric propulsion runs into hundreds. These include cargo vessels, tug boats, ferry boats, dredgers, fire boats, trawlers, self-loading vessels, oil tankers, coastguard cutters, salvage boats, oil barges, yachts, &c. In this paper, I deal with the various methods whereby electric propulsion is applied to the different classes of vessels, and with some matters of arrangement and control, which I hope may be of interest.

Before coming to electric ship propulsion in Great Britain, some remarks regarding the work in this line which has been done in America may be of interest, especially as a much greater tonnage of electrically-propelled vessels has as yet been constructed in the United States than elsewhere. It is generally thought that in America the high scale of wages prevented experiments or initiation in such things as new developments in marine propulsion. This has certainly not been the case in the electric propulsion of ships.

One of the chief reasons for the considerable progress which electric ship propulsion made in the United States was the Jones-White Merchant Marine Act of 1928. This Act was passed in the United States to deal with the decline in merchant shipbuilding in that country after the war, due to the high building costs there as compared with other countries. Under that Act, large mail contracts were placed with American shipping companies, and loans were made at low interest rates for construction of new vessels. Many of the ships built under this stimulus were electrically propelled, and there is little doubt that the example which had already been set by the American Navy helped in this. Up to January 1, 1931, 62 vessels (excluding warships), with turbine electric-drive totalling 867,600 h.p., had been completed or contracted for in the United

States, against nine vessels, having 127,900 h.p., elsewhere. The figures for Diesel-electric were 121 vessels, totalling 88,280 h.p., against eight vessels with 16,700 h.p. in other countries. Of the American figures, some 20 per cent were ordered or under construction in 1930.

ELECTRIC PROPULSION IN THE AMERICAN NAVY.

The most spectacular event in the history of electric ship propulsion was the decision of the American naval authorities to adopt electric propulsion for new battleships and battle cruisers. The first large ship to be thus launched in the year 1917 was the U.S. battleship *New Mexico*. The fact, however, that last year it was decided to change the electric drive on this ship to geared drive is naturally of particular interest to a discussion of this subject, and, at first sight, might appear to constitute a weighty argument against the whole system. On investigation, however, it would appear that such a conclusion would not be correct, and the decision which was taken to make the change confirms the arguments brought forward in this paper.

The *New Mexico* has a displacement of 32,000 tons, and was originally designed for a speed of 21 knots, developing 31,300 shaft horse-power. Two steam turbines were used and four induction type motors. These latter had pole-changing switches giving 24 poles or 36 poles, the generators being 2 pole; the speed reductions were 12 to 1 and 18 to 1, respectively. The reason for the pole-changing devices was to improve the economy at cruising speeds, as then one generator could drive the four motors in parallel. From 17 knots upwards each generator drove the two motors on the same side of the ship. It was not possible to drive the two inboard motors from one generator, or the two outboard motors from the other. The motors were always backed on the 36-pole arrangement, as this gave the higher reversing torque. Ordinary speed variation of the propellers was effected by changing the speed of the turbo-generators, which were quarter-phase, two-pole, 2,100 r.p.m. machines, and provided with switches to change the windings when operating two or four motors, respectively, thereby decreasing the internal copper losses. The motors of the *New Mexico* were of the double squirrel cage type; the slots of the rotor had each two bars,

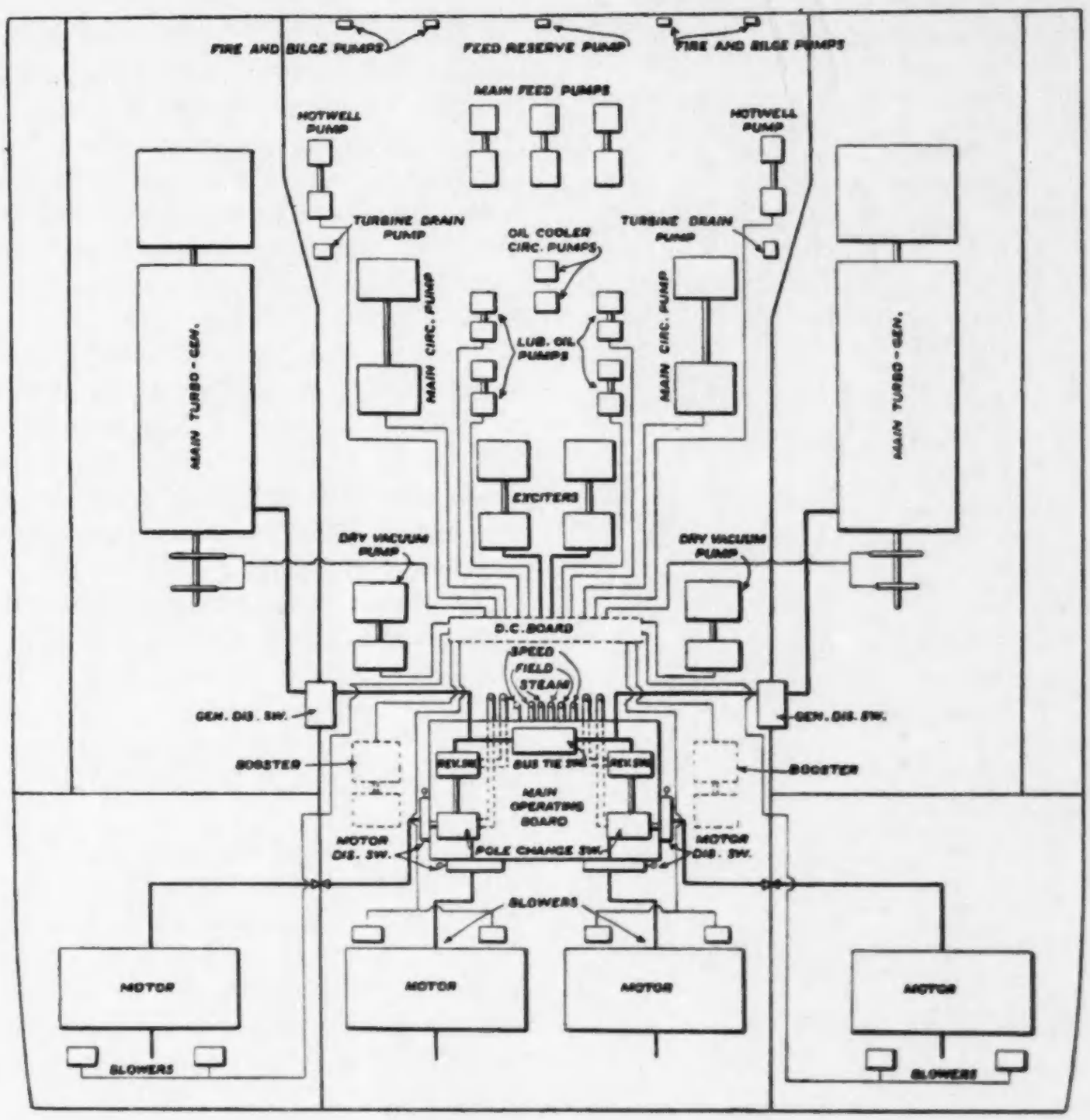


Fig. 1.—U.S.S. "New Mexico"—arrangement of machinery.

the outer one of high-resistance material and the inner one of copper. The copper squirrel cage is the effective one at full speed, and the outer high-resistance bars give the high torque required for reversal. The reversing and pole-changing switches were oil-break, and although large enough to break full load current, this was never done, as the field was always opened before moving them. All reversing was accomplished at low speed and low voltage.

It will be clear from this very abridged description that the switch and interlocking gear of this induction motor type of drive must be relatively very complicated compared with the synchronous motor drive, and the chances of mistakes in operation are greater.

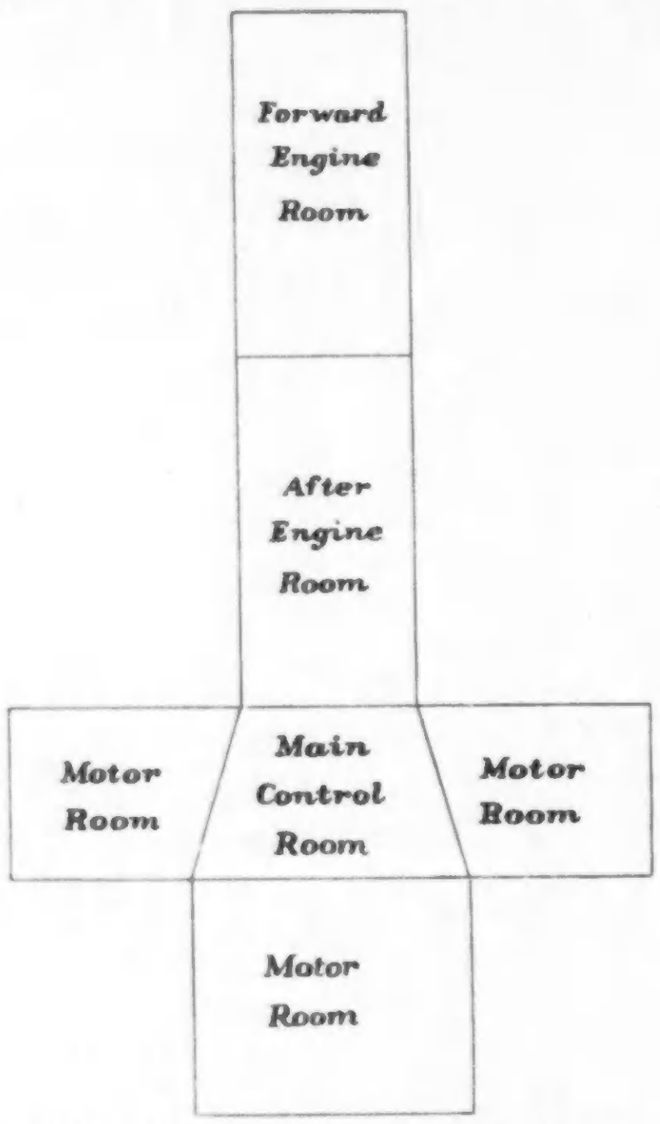


Fig. 2.—U.S.S. "California," "Maryland" and "West Virginia"—arrangement of machinery.

The trials of the *New Mexico* gave the following results :—

Speed.	Water rate.	
Full	12.01	Increase from full to 0.48 speed, 16 per cent.
19 knots	12.33	
15 ,, ...	12.475	
10 ,, ...	13.96	

The main point to be remembered about the *New Mexico* is, however, that she was not designed as an electrically propelled ship at all. This is very clear from a comparison of the machinery layout of the *New Mexico* (fig. 1) with that of the U.S.S. *California, Maryland,* and *West Virginia* (fig. 2).* The latter ships were originally designed to use electric propulsion, and the more economical layout is obvious. In 1931 it was decided to increase the horse-power of the *New Mexico, Mississipi* and *Idaho*† by some 8,000 shaft horse-power, and tenders were invited for new equipment of either the geared turbine or turbo-electric type. The American Navy Department had no fault whatsoever to find with the previous electrical equipment of the *New Mexico* which had been perfectly satisfactory. The decision to change over to the geared drive was made simply on the tenders received. These were in the following proportion :—

Firm A—Geared turbines ..	100	per cent.
Electric drive	165	,,
Firm B—Geared turbines ..	156	,,
Electric drive	206	,,

It is somewhat difficult to reconcile these tenders made by firms of equal standing. The large discrepancy between the prices of the two tenderers prevents any definite conclusion being drawn as to the relative costs of the electric and geared drives, as it will be seen that the price of the electric drive of Firm A is near that of the geared drive of Firm B. It is clear, however, that no general conclusion of the relative merits of the turbo-electric and geared turbine systems can be drawn from the decision which the Bureau of Engineering at Washington had to make on the basis of these tenders. The question of the adoption of electric ship propulsion must be decided in each case upon the design of the ship as a whole. The *New Mexico* was originally designed as a single-reduction geared turbine ship, and it was to be expected that geared turbines would give the better results. To install the electric drive in a vessel not designed for it was doubtless a mistake.

As the American naval vessels are the outstanding examples of the turbine induction motor system, some further details of these other electric ships are given below.

The *California, Maryland* and *West Virginia* were very similar to the *New Mexico,* but are specially designed electric ships. They have the same horse-power as the *New Mexico,* but their turbines have downward exhaust instead of upward. As regards the electrical machinery, practically the only difference from the *New Mexico* is the rotor of the propulsion motors. This has a definite winding combined with a high-resistance squirrel cage, both being located in one slot. For reversing, a contactor opens the definite winding, the stator being connected in the 36-pole condition. When the motor is at full speed the definite winding is short-circuited. If the motors are backing, only the 36-pole connection can be used ; but if they are ahead, then the 24-pole arrangement can be employed, if desired. It will be seen that this type of motor requires a switch in the rotor winding as well as the pole-changing switches in the stator winding.

* Figs. 1 and 2 are taken from Commander S. M. Robinson's book, *Electric Ship Propulsion.*

† The Mississipi and Idaho were not electric ships, but originally had direct-coupled turbines. They were changed to single-reduction geared turbines to bring all three ships into line with the increased horse-power.

The *Tennessee, Colorado* and *Washington* are practically sister ships of the *California,* and the general arrangements of the machinery are similar. The main motors are three-phase with two independent windings of 24 poles and 36 poles. The rotors are of the definite-wound type and act as a definite winding for the 24-pole arrangement of the stator and as a squirrel cage with the 36-pole stator winding. Reversing is effected with the 24-pole arrangement. The rotor windings are taken to slip-rings which connect them to liquid rheostats.

The change-over from 24 poles to 36 poles takes place automatically in the rotor winding. It will be seen that the large torque necessary for reversing is provided by the use of external rotor resistances. The liquid rheostat consists of two tanks, the electrolyte (sodium carbonate solution) being circulated from the lower to the upper tank by a pump, and the lower tank is cooled by a cooling coil. When the electrolyte is at the highest point the whole rheostat is shorted by the short-circuiting switch. All the alternating-current switches are of the oil-immersed type, some being provided with vertical disconnecting plugs to facilitate removal for cleaning and overhauling. The control gear is relatively complicated, there being 19 operating levers.

The airplane-carriers *Lexington* and *Saratoga* are the largest electrically propelled ships in the world. The *Lexington* was originally designed for a battle-cruiser, but work on her was suspended in February, 1922, upon the signing of the Washington Treaty for the Limitation of Armaments. Work was renewed a few months later on her conversion, in accordance with the terms of the treaty, to an aircraft-carrier. The U.S.S. *Saratoga* is a similar vessel and was launched in 1925. Their normal displacement is 33,000 tons, and speed 33 knots. Steam is raised by 16 oil-fired boilers, each of 14,500 sq. ft. heating surface, and each has four 35,200-kW, 40,000 kVA turbo-generators running at 1,755 r.p.m., 5,000 volts. There are four pairs of propulsion motors totalling 180,000 shaft horse-power, each pair driving one of the four propellers, which turn at 317 r.p.m. at full speed. The motors have rotors provided with a high resistance squirrel-cage winding at the bottom of the slots for starting and phase wound for regular operation. The stator winding has 44 poles for low speeds and 22 poles for high speeds. Slip-rings are provided in the latter winding, which are short circuited in the 44 pole connection.

The *Lexington* and *Saratoga* are interesting, as the electric drive was not used mainly with the idea of steam economy. The auxiliaries were steam-driven, which, of course, is the reverse of economical. Everything was, in fact, sacrificed to space and weight; nevertheless, electric propulsion was adopted. The speed records obtained on the completion of the vessels justified in that respect, at least, the choice made by their designers.

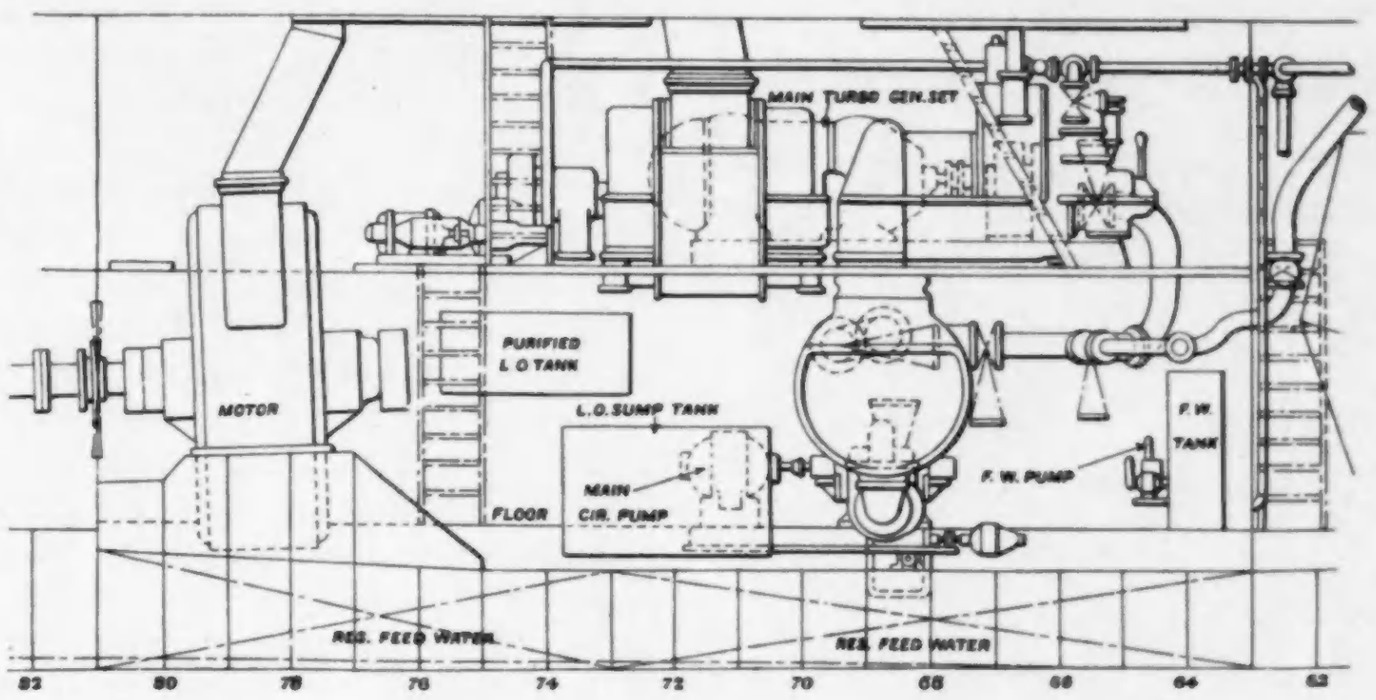


Fig. 3.—Engine room layout of Lake class coastguard cutters.

Electric propulsion has also been adopted for a considerable fleet of coastguard cutters in the United States. The engine-room layout of such a vessel is shown in fig. 3. The single propulsion motor of the synchronous type is rated at 3,000 h.p., 2.300 volts, three-phase, 60-cycle, 163½ r.p.m., and receives its power from a single turbo-generator rated at 2,600 kW, 3,600 r.p.m. All auxiliaries are electrically driven and take their power from the main turbo-generator. At full power the speed is 16½ knots. It is claimed that these vessels can put out to sea under weather conditions impossible for other classes of ships.

OCEAN-GOING LINERS.

For electrically propelled, ocean-going liners the turbo-electric system has been most general hitherto, although the Diesel engine is not out of the question, and synchronous propulsion motors are usually used. The advantages of the electric system for such ships may be summarised as follows:—

1. Increased overall efficiency.

2. Higher speeds can be obtained under heavy sea conditions.

3. Flexibility in the location of the machinery assists in the disposition of the weights for proper trim, lessens the amount of steam pipes, avoids long propeller shafts, allows condensers to be placed vertically below turbines, improves ventilation, and lessens congestion.

4. Lessens vibration and noise; increased comfort for passengers and crew.

5. Increased safety by allowing better subdivision by watertight compartments, and disablement of part of the prime movers does not vitally affect working of the ship.

6. Avoids reversing turbines and cushioning effect of air gap of electric machinery substituted for the varying pressure on the teeth of the gears.

ELECTRIC PROPULSION USING ALTERNATING CURRENT.

Alternating-current generators, if they are to be of light weight and small diameter, have to be driven at

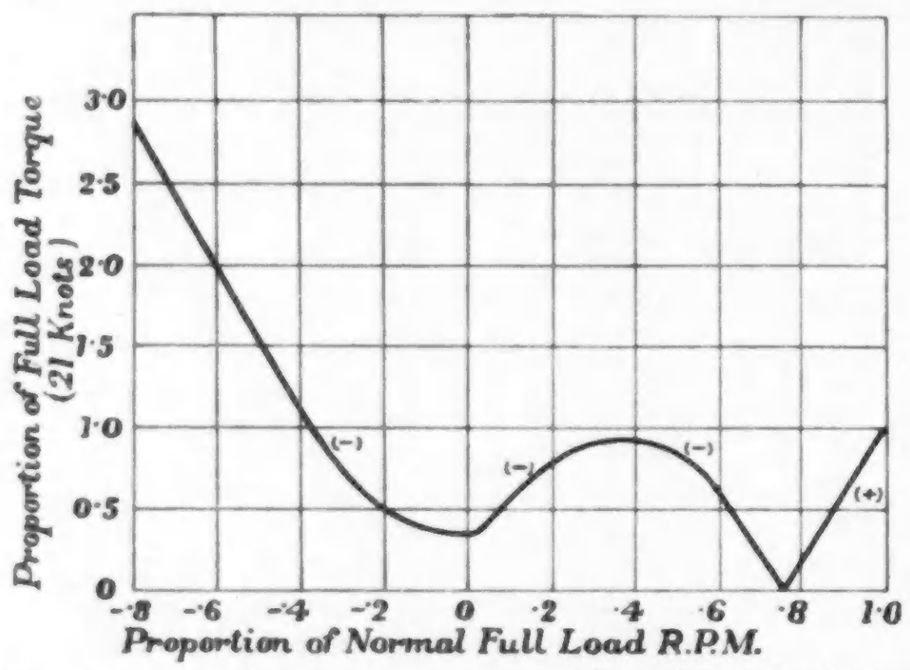


Fig. 4.—Propeller torque curves, ship going ahead at constant full speed.

speeds of 1,500 r.p.m. or 3,000 r.p.m. If such electric generators are to be used, then the only prime movers which can be considered are steam turbines, and the only comparison we have to make is that between the geared turbine and the turbo-electric system. In such a comparison only ships exceeding, say, 3,000 shaft horse-power come into consideration. As regards efficiency of the drive at full load, there is very little difference, the single-reduction mechanical gear being slightly more efficient and the double reduction gear less efficient than the turbo-electric drive; this comparison only applies to full-speed conditions. At lower speeds, however, the efficiency of the electric drive will be much higher than the mechanical gear, due to the inherent higher efficiency under these conditions, and to the fact that one (or more) turbines can be shut down while feeding all the screw motors in parallel from the lesser number of prime movers. This renders the electric drive very suitable for a vessel which runs at different times on varying schedules. With synchronous motors, the speed of the turbo-generator bears a constant ratio to the propeller revolutions per minute. At low power, the propellers are running slowly, but the power required to drive them falls off more quickly than their speed. Hence the power delivered by the lesser number of turbo-generators, even though these are running at reduced speed, is sufficient to drive the ship, and the waste of running the larger number of turbines at still lower individual power is avoided.

PROPELLER TORQUE CHARACTERISTICS OF ELECTRICALLY PROPELLED VESSELS.

Naturally, the maximum duty imposed upon a propulsion equipment is to reverse the ship when travelling at full speed in the ahead direction. Fig. 4 illustrates the torque exerted on the propeller shaft under these conditions, the speed of the ship being constant in the ahead direction. In the first moment of reversal, forward power is removed from the propeller shaft, and the revolutions per minute fall suddenly to about 70 per cent of the revolutions per minute corresponding to full speed. In other words, the way of the ship keeps the alternator revolving at 70 per cent revolutions per minute without any driving torque being applied. A reversing torque is now applied to the propeller shaft, and this has to be continually increased until the revolutions per minute of the propeller (still revolving in the ahead direction) are about 40 per cent of the full revolutions per minute. At this number of revolutions per minute, the reverse torque is about equal to full load torque. In other words, to reduce the revolutions per minute of the propeller shaft to 40 per cent of the full-speed revolutions per minute, a reverse torque exceeding full-load torque has to be applied to the propeller shaft, the ship itself meanwhile maintaining constant speed through the water. Having reduced the revolutions per minute to 40 per cent, the reverse torque required to reduce the revolutions per minute to zero is smaller than full-load torque until the direction of rotation of the propeller is actually reversed, when the necessary torque increases with the speed of the propeller in the reverse direction. During this process, of course, the vessel has been losing way, and once the propeller has been reversed, the actual reversal of the ship follows. It is clear, however, that if the propulsion equipment cannot exert a reversing torque while the propelling motor is rotating at 40 per cent of full speed in the forward direction, it would never reverse the propeller at all.

The foregoing conditions are rendered more difficult in the case of multi-screw vessels if turning be taking place. When turning, the power on the screw on the outboard side of the turning circle drops, and that on the screw on the inboard side of the turning

circle rises. It will, of course, be understood, that if manœuvring is to be done quickly, the propulsion equipment must possess an excess of manœuvring torque over and above the theoretical minimum, and in order to meet all conditions, it must be able to exert this excess torque upon the propeller shaft under all conditions of speed of the latter.

TURBO-ELECTRIC PROPULSION USING SYNCHRONOUS INDUCTION MOTORS.

The three-phase salient-pole synchronous type propulsion motor, shown in fig. 5, which is largely used for turbo-electric ship propulsion, runs, under normal conditions, synchronously with the turbo-generator, with an electrical periodicity of 50 periods per second. The periodicity of 50 is chosen for the same electrical and magnetic considerations as have caused that periodicity to be standardised for land purposes. The motor voltage is generally about 3,000 volts between phases, and the machines are usually wound three-phase, necessitating, of course, three main cables. A synchronous motor has to be excited by direct current, it being, in fact, in this respect, the exact reverse of an electric alternator. A synchronous motor, as such, cannot be self started, its synchronous torque only existing when it is running in synchronism. To make it self-starting it has an asynchronous motor winding added to it. This consists of a high-resistance squirrel-cage winding embedded in the pole faces of the machine. On applying an alternating current to the stator, a current is induced in this winding which provides the starting torque and the large torque required for reversing, during which operation the motor is running asynchronously. The required torque is obtained by a suitable design of the squirrel-cage winding. It is, of course, not possible to apply the full voltage of the alternator to the terminals of such a motor suddenly. To make the connection for starting or reversing, the speed of the alternator is reduced, say to one-fifth full speed, and the excitation of the generator (the motor being unexcited) gradually increased from zero to full value, and, in fact, super-normal generator excitation is applied momentarily. A gradually increasing current flows into the motor, which runs up in speed. Presently, nearly synchronous speed, corresponding, of course, to the reduced speed of the turbo-generator, is attained, whereupon the field switch of the motor is closed, which applies direct-current excitation to its salient poles. It may be mentioned that the motor is said to have salient poles because its field windings are arranged on separate distinct cores, forming respectively north and south poles, like an ordinary

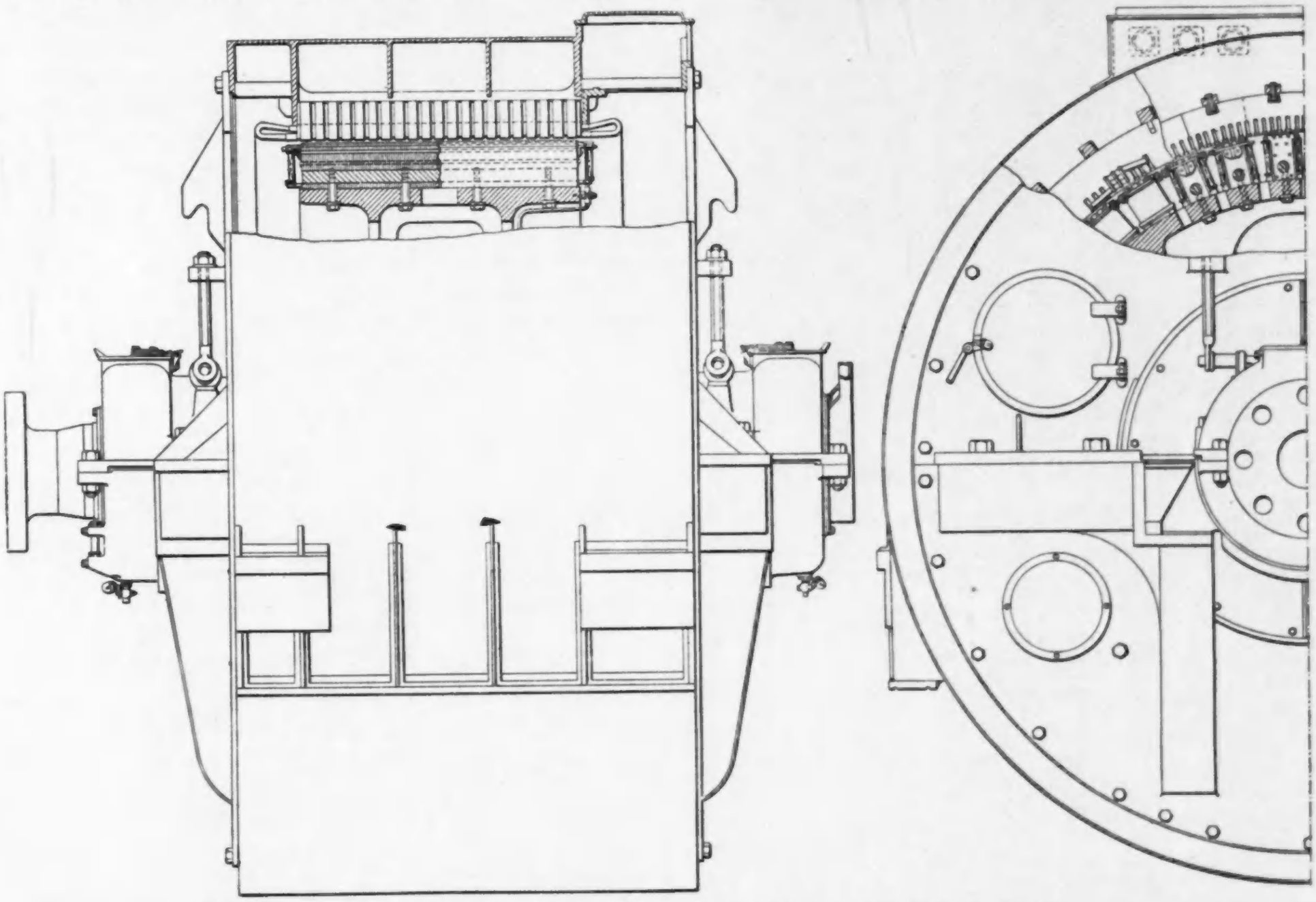


Fig. 5.—Sectional views of salient pole synchronous marine propulsion motor.

direct-current dynamo. This is in contradistinction to the non-salient pole machine, in which the direct-current exciting windings are placed in slots in the circumference of a rotor of uniform circular cross section. The salient pole machine has speed torque characteristics which render it very suitable for marine service.

The result of exciting the field winding of the rotating propeller motor is to cause a synchronising torque to come into existence, which pulls the machine into electrical synchronism. By adjustment of the field winding, the current taken by the motor can be regulated for unity power factor, this being, in fact, one of the chief advantages of this type of motor.

For large passenger vessels and high-speed freight carriers, this type of propulsion is highly efficient, and as the electric machinery works at unity power factor the cost of the plant is reduced. Further, a speed of 75 per cent of the maximum can be obtained with half the main generating plant shut down, and thus with no sacrifice of efficiency.

CONTROL GEAR FOR TURBO-ELECTRIC DRIVE WITH SYNCHRONOUS MOTORS.

This being what may be regarded as the standard method of ship propulsion for large commercial vessels, a short description of the principles underlying the method of control, upon

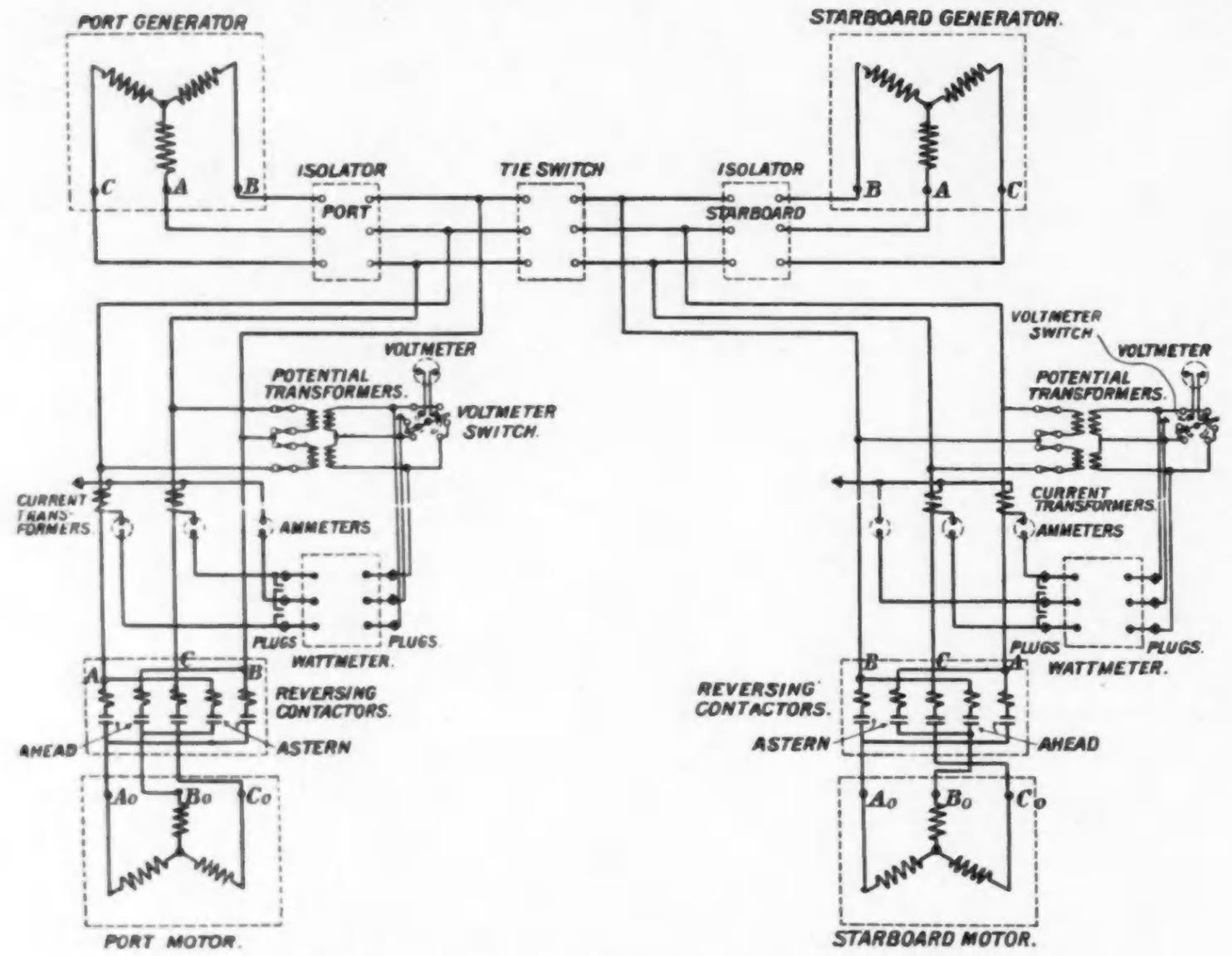


Fig. 6.—Propulsion circuits; S.S. "Viceroy of India."

Further, it continues to follow the speed of the main turbine exactly. There is no varying slip, depending on the load, as with an induction motor; thus the relative speeds of the propellers can be very accurately adjusted. If two screws derive power from one alternator, then their speeds always remain exactly the same.

Speed variation is obtained by varying the speed of the steam turbine. This method of propulsion is suitable for large commercial vessels which operate continuously on definite routes. In such vessels it is of little economic importance to use power from the main units for auxiliary purposes; they are, in fact, generally provided with special auxiliary generators which are of a sufficient size as to be reasonably efficient.

which a great deal of the success of the installation depends, may be of interest. Compared with the direct current drive, the use of alternating current machinery necessarily introduces certain complications. It is all the more necessary, therefore, to give the problem the closest study in order to simplify, and therefore render the routine operations of driving the vessel the more safe. It was mentioned above that for the main control of the battleship *Tennessee*, having four motors and two generators (total rated shaft horse-power 29,000), 19 operating levers are required. Against this may be set the *Monarch of Bermuda*, which has likewise four motors and two generators (total shaft horse-power 19,000), but the control of which has been reduced to four operating hand-wheels, the turning of which

performs all the operations of starting and reversing the ship. As is generally the case in such ships, the controls of the *Monarch of Bermuda* are exercised in the engine room under telegraphic communication from the bridge. It will be realised that if, in such ships, bridge control is to be adopted, then the reduction of the number of operating hand-wheels, or levers, to a minimum is essential.

P. & O. TURBO-ELECTRIC LINER "VICEROY OF INDIA."

The *Viceroy of India* is a twin-screw liner of 19,050 tons displacement, with two turbo-generators, the electrical equipment being made by The British Thomson-Houston Company, Limited. The two motors are of the salient-pole, synchronous type, each capable of developing 8,500 shaft horse-power. The general diagram of connections is given in fig. 6, and a photograph of the main electrical control board is shown in fig. 7. It will be seen that the control is by means of six levers (three per turbine). The functions of these levers are successively as follows :—

1. To vary turbine speed from 3,110 r.p.m. down to about 700 r.p.m. during the first half of the travel of the appropriate lever ; during the second half of its movement the lever operates a camshaft which opens and closes contactors for regulating the motor and alternator fields. At the end of its travel both fields are open-circuited. Thus, complete control of the speed is given by the lever No. 1.
2. To reduce speed down to 110 r.p.m.
3. For reversing. This can only be operated when all field circuits are switched off.

Starting is effected by running the turbine up to 700 r.p.m. and moving No. 1 lever to its first notch. This closes and over-excites the alternator field, so that the motor starts as an induction motor. On the second notch the motor field is excited and the motor is pulled into synchronism with the alternator, and the field of the latter is then reduced to normal.

Fig. 6 shows how both motors can be run from only one alternator by the use of machine isolating and tie switches. These are operated by hand-wheels so interlocked that only two can be closed at one time. In addition to the levers mentioned above, there are hand-wheels for controlling the excitation of the propeller motors.

In order to secure the advantage of quick closing given by electric contactors with the reliability of mechanical operation, The British Thomson-Houston Company (B.T.-H. and Watson's British Patent 276,085) use an arrangement of a series of cams mounted on the shaft, or geared thereto, of the master control switch for the contactors. Rotation

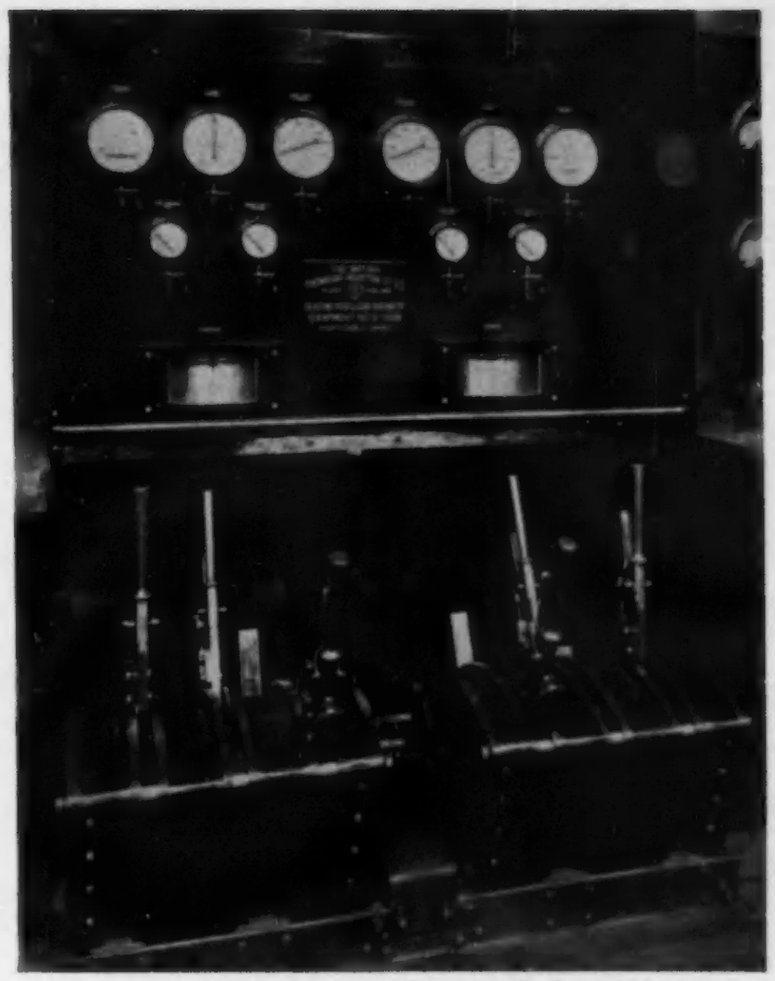


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Fig. 7.—Main control board ; S.S. "Viceroy of India."

of the shaft first closes the circuit of the closing coil of the contactors and at the same time brings the corresponding cam into such a position that the contactor is held closed by this means, after the circuit of its closing coil is broken.

Should, for any reason, the contactor closing coil fail to function, then the contactor is mechanically operated by the cams alone. The latter, therefore, operate as a stand-by to the purely electrical working. A record taken on the trials of the vessel is given in fig. 8.

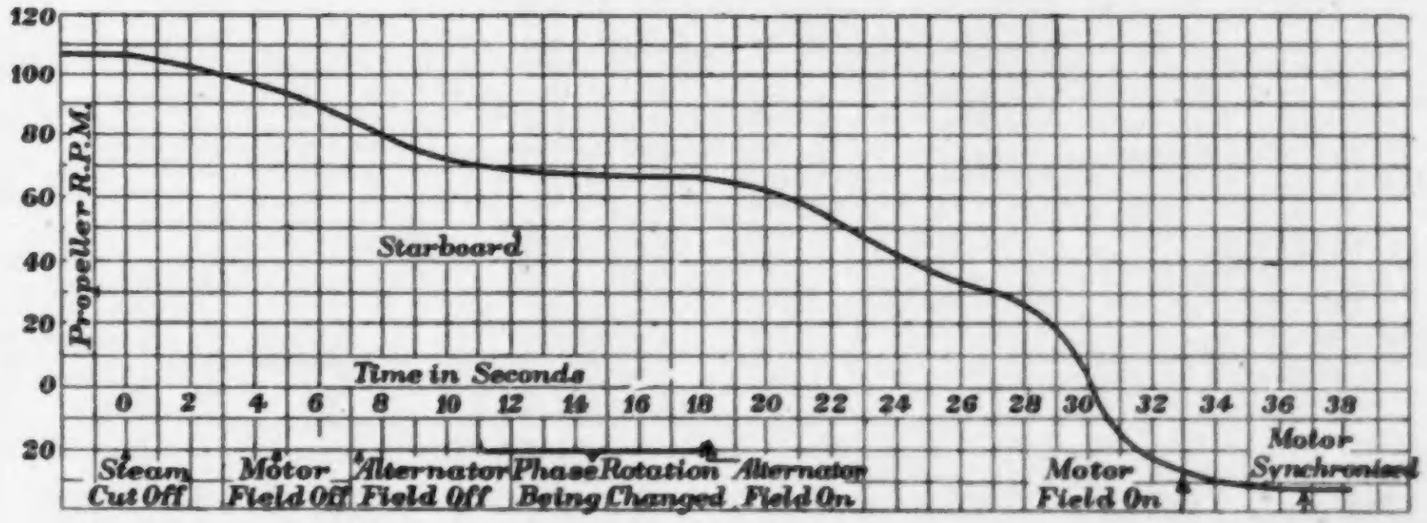


Fig. 8.—Full speed reversal on trials of S.S. "Viceroy of India." Reversal made at 18.5 knots ; displacement 19,000 tons ; ship stopped in 2 minutes 10 seconds.

THE "MONARCH OF BERMUDA."

This vessel is the first quadruple-screw, electrically-propelled passenger liner built. The pro-

pulsion system is turbo-electric, using synchronous salient-pole induction motors. There are two 7,500 kW turbo-generators and four motors each of 4,750 h.p.

The whole of the propulsion and other electric equipment was supplied by The General Electric

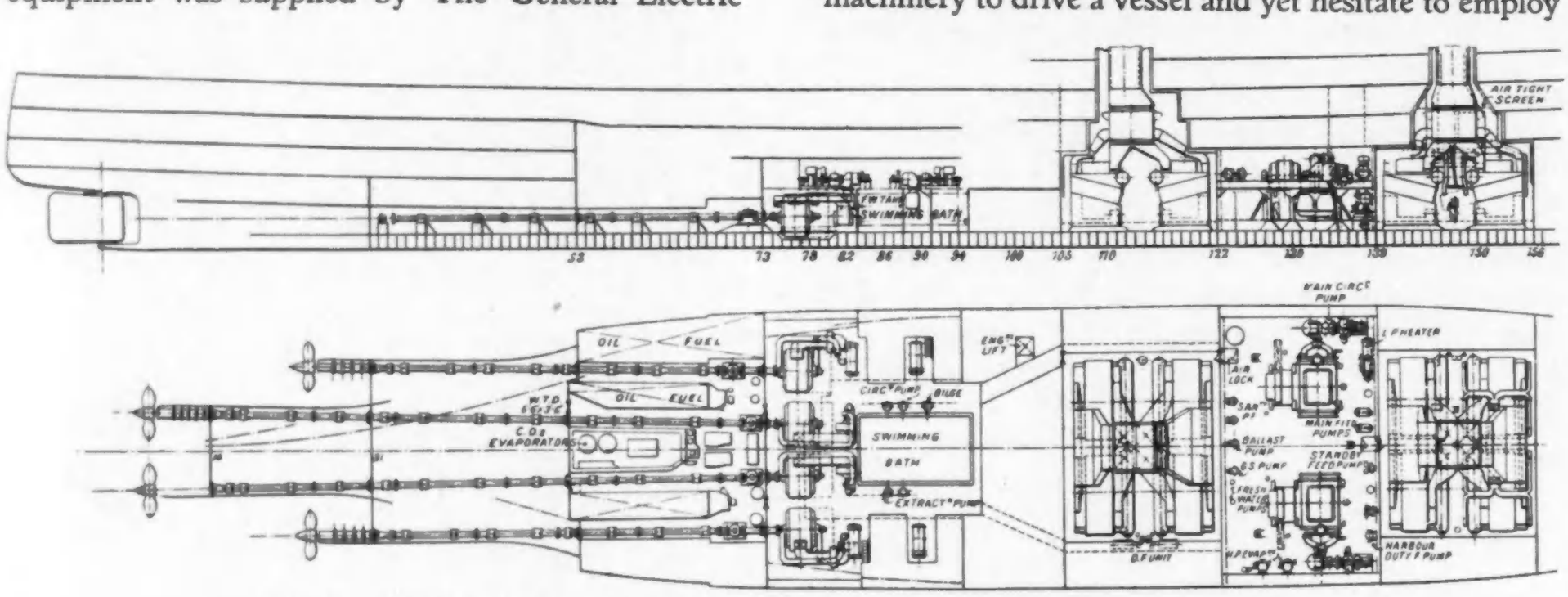
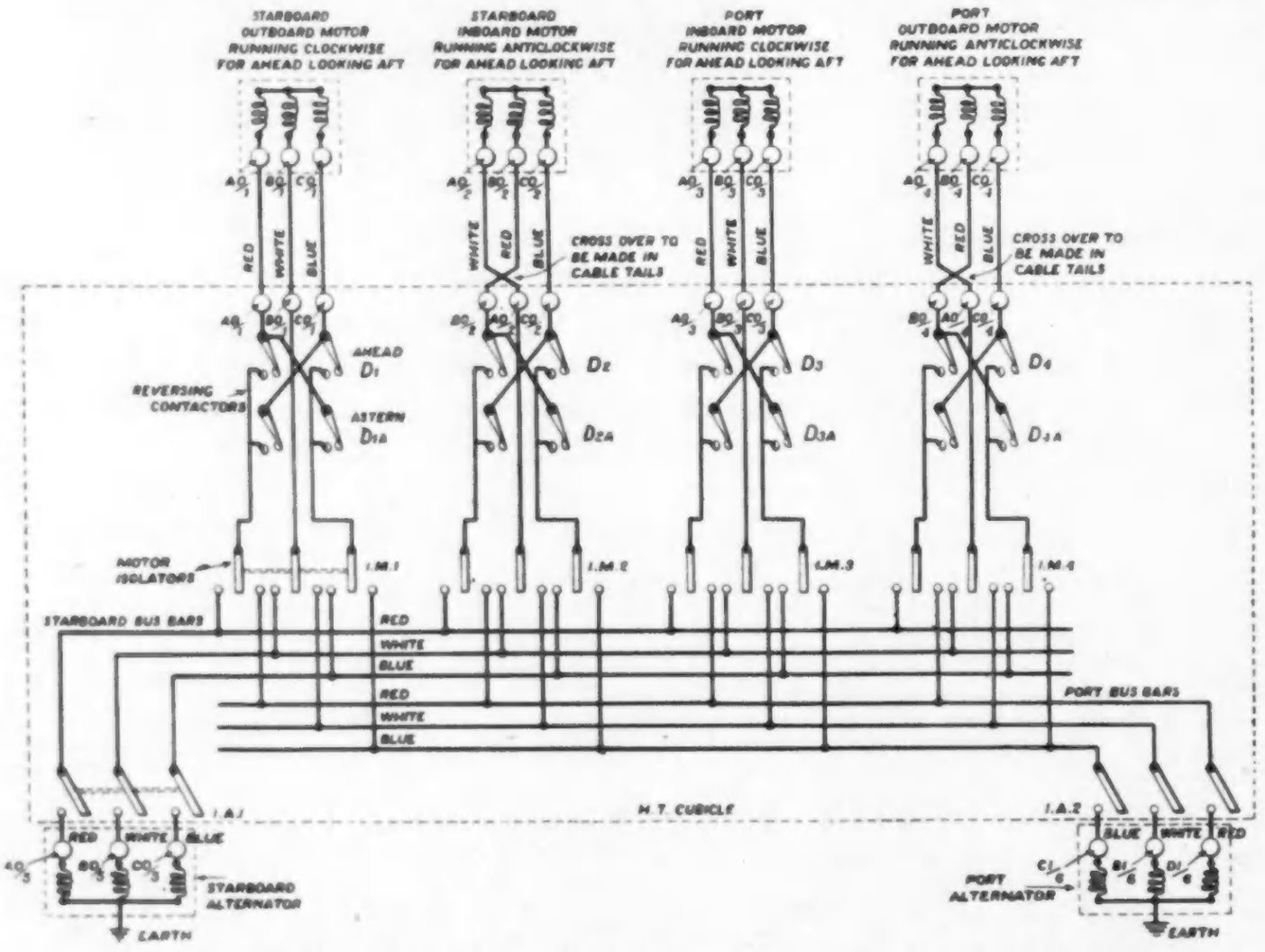


Fig. 9.—Q.T.E.V. "Monarch of Bermuda"—general arrangement of machinery.



AO/1, BO/1, CO/1 Starboard outboard motor stator terminals.
AO/2, BO/2, CO/2 Starboard inboard motor stator terminals.
AO/3, BO/3, CO/3 Port inboard motor stator terminals.
AO/4, BO/4, CO/4 Port outboard motor stator terminals.
AO/5 Alternator stator phase red
BO/5 Alternator stator phase white
CO/5 Alternator stator phase blue (Starboard.)
A1/6 Alternator stator phase red
B1/6 Alternator stator phase white
C1/6 Alternator stator phase blue (Port.)
D1 Starboard outboard motor direction contactor
D2 Starboard inboard motor direction contactor
D3 Port inboard motor direction contactor
D4 Port outboard motor direction contactor (For ahead running.)
D1a Starboard outboard motor direction contactor
D2a Starboard inboard motor direction contactor
D3a Port inboard motor direction contactor
D4a Port outboard motor direction contactor (For astern running.)
1M1 Starboard outboard motor isolator.
1M2 Starboard inboard motor isolator.
1M3 Port inboard motor isolator.
1M4 Port outboard motor isolator.
1A1 Starboard alternator isolator.
1A2 Port alternator isolator.

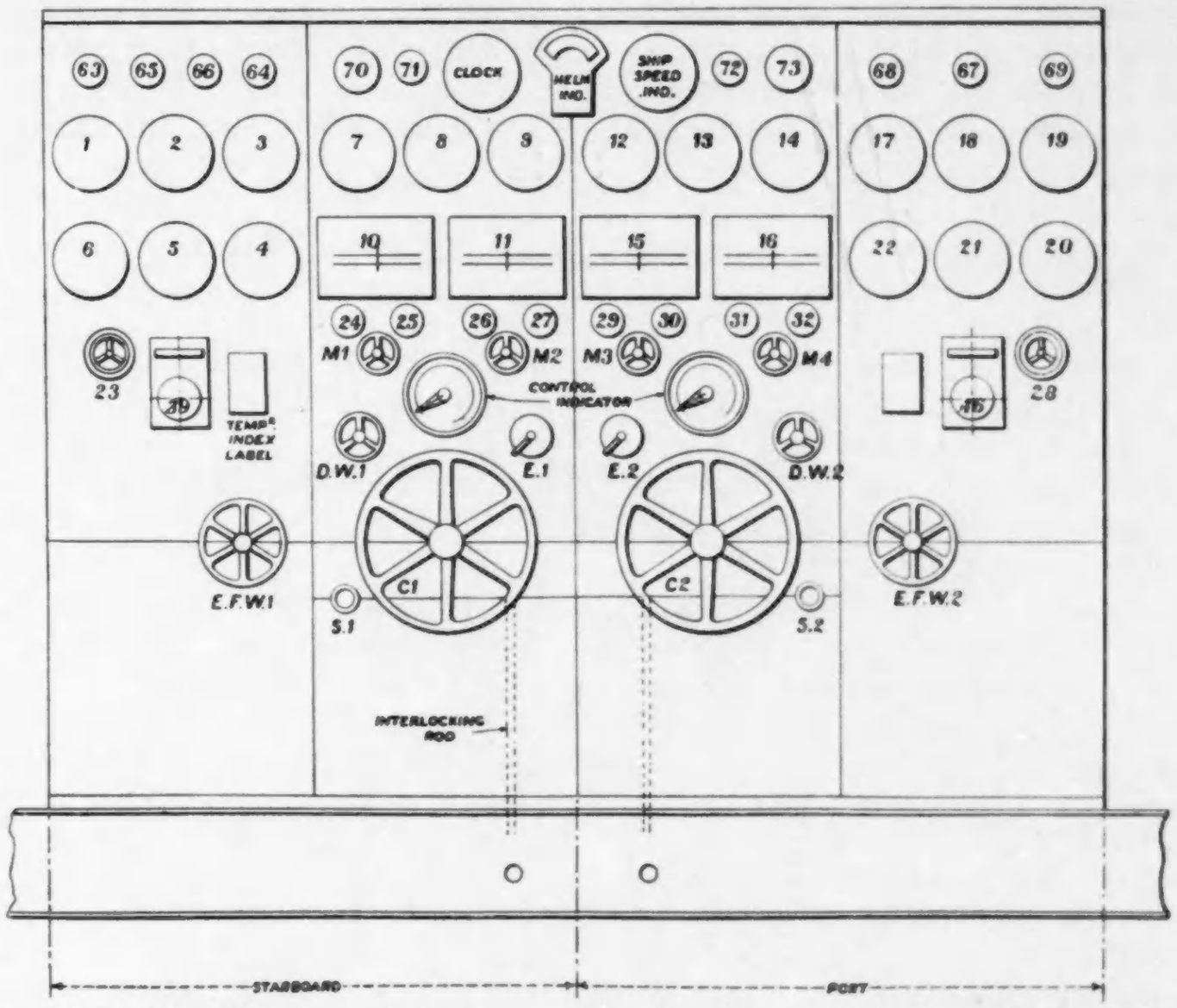
Fig. 10.—Diagram of 3-phase stator circuits, Q.T.E.V. "Monarch of Bermuda."

Company, Limited, and embodies many interesting features. In particular, the system of control is novel, allowing, as it does, a complete series of combinations between the motors and the generators, with a very marked reduction in the number of control hand-wheels. This result has been rendered possible by the use of a large measure of automatic electric control. In some quarters it has been considered that automatic electric control is not sufficiently reliable for marine purposes. This idea underlies the design of the combined electric and cam-operated contactor referred to above. But land practice with automatic electric stations, has shown conclusively that automatic operation is more reliable than hand working. Further, it can only be regarded as irrational to adopt electric machinery to drive a vessel and yet hesitate to employ all the advantages which electric control brings in its train. The engineers responsible for the design of the control gear for the *Monarch of Bermuda* determined, therefore, to disregard all previous mistrusts and to go as far with automatic electric working as the circumstances permitted. The extreme flexibility which has resulted adds, there can be no doubt, very considerably to the safety of the vessel.

In addition to these inherent advantages of the electric control, a system of emergency control has been provided which can be put into use should the

automatic system fail. It will thus be seen there is a number of safeguards capable of dealing with several successive breakdowns, so that a total disablement of the vessel, due to failure of the electrical machinery, is a very remote possibility. Fig. 9 will give an idea of the arrangement of the electrical machinery in the vessel.

two outboard motors from the other. When running lower than full speed, of course, one turbo-alternator is shut down and four (or any less number) of motors are supplied by the other generator. It must be borne in mind that whatever combination of machinery is used, the same pair of main control wheels and pair of reversing hand



1	Starboard Outboard Motor Wattmeter.	23	Starboard Booster Field Regulator.	68	Port Inboard Fan Running Lamp.
2	,, Stator Voltmeter.	24	,, Outboard Astern	69	,, Outboard Fan Running Lamp.
3	,, Inboard Motor Wattmeter.	25	,, Outboard Ahead	70	Starboard Excitation Alarm Bell.
4	Alternator Field Voltmeter.	26	,, Inboard Astern	71	,, ,, ,, Lamp.
5	,, Stability Indicator.	27	,, Inboard Ahead	72	Port Excitation Alarm Lamp.
6	,, Alternator Field Ammeter.	28	Port Booster Field Regulator.	73	,, ,, ,, Bell.
7	,, Outboard Motor Stator Ammeter.	29	,, Inboard Astern	M1	Starboard Outboard Motor Contactor Switch.
8	,, Alternator Ammeter.	30	,, Inboard Ahead	M2	,, Inboard Motor Contactor Switch.
9	,, Inboard Motor Stator Ammeter.	31	,, Outboard Astern	M3	Port Inboard Motor Contactor Switch.
10	,, Outboard Speed Indicator.	32	,, ,, Ahead	M4	,, Outboard Motor Contactor Switch.
11	,, Inboard Speed Indicator.	39	Starboard Temperature Indicator.	DW1	Starboard Direction Wheel.
12	Port Inboard Motor Stator Ammeter.	46	Port Temperature Indicator.	DW2	Port Direction Wheel.
13	,, Alternator Ammeter.	63	Starboard Outboard Fan Running Lamp.	E1	Starboard Emergency Switch.
14	,, Outboard Motor Stator Ammeter.	64	,, Inboard Fan Running Lamp.	E2	Port Emergency Switch.
15	,, Inboard Speed Indicator.	65	,, Booster Running Lamp.	EFW1	Starboard Emergency Field Switch.
16	,, Outboard Speed Indicator.	66	Spare Booster Running Lamp.	EFW2	Port Emergency Field Switch.
17	,, Inboard Motor Wattmeter.	67	Port Booster Running Lamp.	S1	Starboard Starting Valve.
18	,, Stator Voltmeter.			S2	Port Starting Valve.
19	,, Outboard Motor Wattmeter.			C1	Starboard Main Control.
20	,, Alternator Field Voltmeter.			C2	Port Main Control.
21	,, Stability Indicator.				
22	,, Alternator Field Ammeter.				

Fig. 11.—Front of control cubicle, Q.T.E.V. "Monarch of Bermuda."

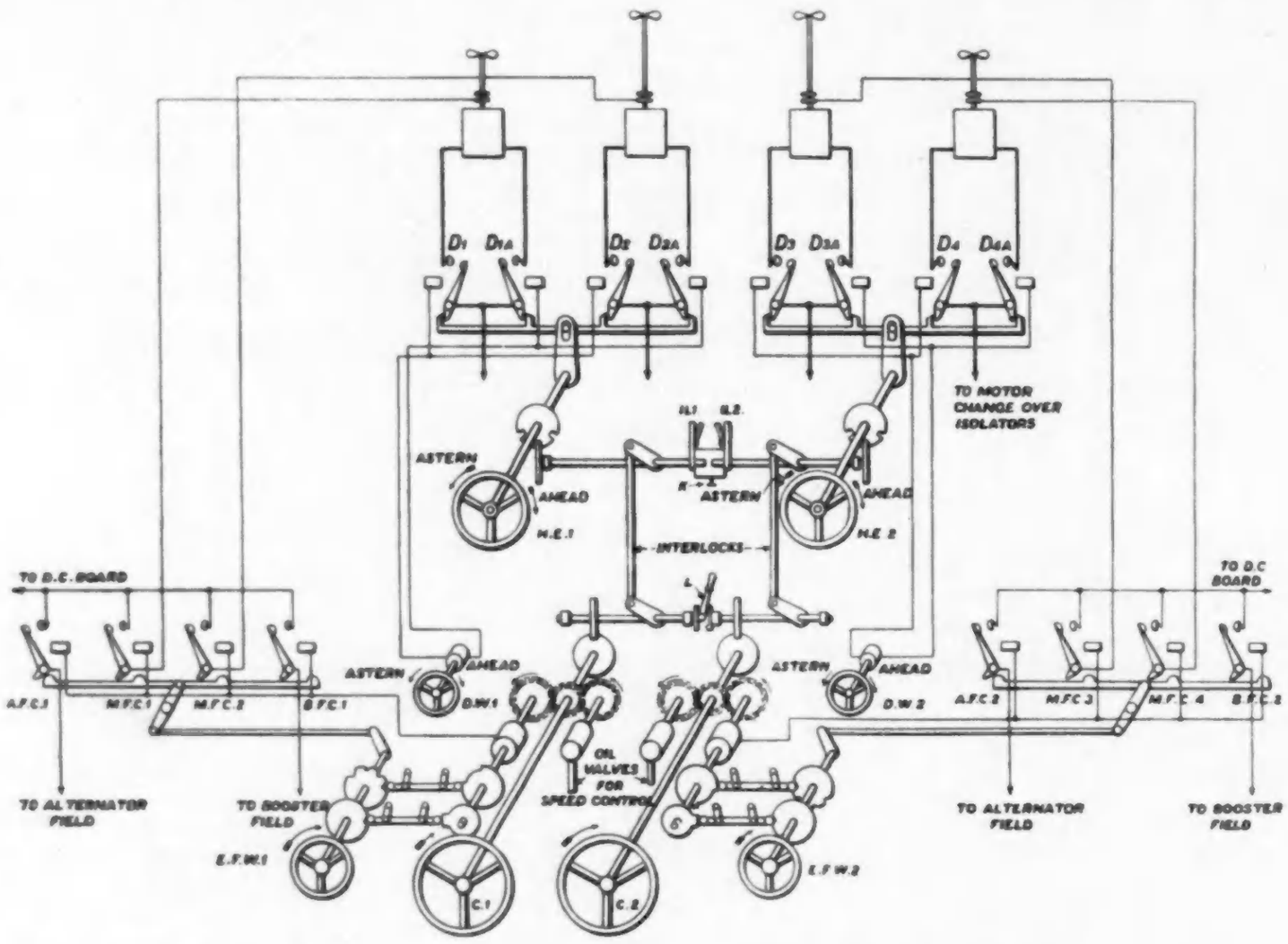
A diagram of the main power circuit connections is given in fig. 10. From this it will be seen that any motor can be connected to either alternator, but it is not possible to parallel the two alternators. Normally, when running at full power, the two starboard motors are connected to the starboard alternator, the port machinery being similarly connected. But an important alternative arrangement is possible which is particularly useful in rough weather to equalise the loads on the alternators; this is to run the two inboard motors from one alternator and the wheels perform all the control. The use of automatic switchgear allows all connections to be arranged automatically so that the operation of control remains unaltered no matter how the machinery is connected.

It has been mentioned, in the case of the American naval vessels, that oil-immersed switches were extensively used for making and breaking the main connections. Present practice, which has been followed in this vessel, however, is to use airbreak contactors. While the latter obviate the

fire risk due to the presence of oil, which is, however, but small, their chief advantage is that they are more accessible, and the contacts are more durable. Practically all arcing at the contacts is obviated by carrying out all switching operations with the field circuits of the machines broken. Thus, but small currents (due to remanent magnetism in the generators and motors) are actually made and broken. Owing to the fact that the magnetic field of an electric machine does not die away instantaneously when its field circuit is broken, care must be taken that there is a short time interval (amounting to a few seconds) between the rupturing of the field circuit and the operation of the main contacts. This time interval, on the *Monarch of Bermuda*, is arranged to take place automatically. The main control board of this vessel is illustrated in fig. 11.

Under ordinary running conditions, the whole control is exercised through the four handwheels DW1, DW2, C1 and C2. DW1 and DW2 pre-select the connections for ahead or astern working, everything else, such as starting up and speed control, is done by the wheels C1 and C2. The several other wheels on the board are extraneous to the normal control. Their functions can be seen from the table attached. Handwheels M1, M2, M3 and M4, are only effective when the main control wheels are at "stop." If they are then turned they cut off the corresponding motor circuits. The booster field regulators 23 and 28 are only required in heavy weather to increase the excitation of the alternators above the normal. The emergency field wheels EFW1 and EFW2 are used in connection with the emergency operating gear to be described later.

For starting to full ahead the turbines are first run at very low speed ($\frac{1}{12}$ full speed), by opening the starting valves S1 and S2, and the wheels DW1 and DW2 are put in the ahead position. The main control wheels C1 and C2 are then moved in a clockwise direction to the "dead slow" position, at which the ahead contactors D1, D2, D3 and D4 close automatically. The first half revolution of the wheels C1, &c. increases the steam supply, so that the turbines run up to one-fifth speed, and at the end of this half revolution the alternator field contactors close automatically. A sequence catch arrests movement of the wheel at this point. The full direct-current voltage of 220 volts is thus applied to the alternator



D1	Starboard outboard motor direction contactor	} For	
D2	,, inboard ,, ,, ,,	ahead	
D3	Port ,, ,, ,, ,,	run-	
D4	,, outboard ,, ,, ,,	ning.	
D1a	Starboard outboard motor direction contactor	} For	
D2a	,, inboard ,, ,, ,,	astern	
D3a	Port ,, ,, ,, ,,	run-	
D4a	,, outboard ,, ,, ,,	ning.	
IL1	Starboard locking lever.		
IL2	Port locking lever.		
K	Castell Key.		
HE1	Emergency wheel for starboard direction contactors.		
HE2	,, ,, port ,, ,,		
L	Clutch lever.		

DW1	Starboard direction wheel.
DW2	Port direction wheel.
AFC1	Starboard alternator field contactor.
AFC2	Port alternator field contactor.
MFC1	Starboard outboard motor field contactor.
MFC2	,, inboard ,, ,,
MFC3	Port ,, ,, ,,
MFC4	,, outboard ,, ,,
BFC1	Starboard booster field contactor.
BFC2	Port booster field contactor.
EFW1	Starboard emergency field wheel.
EFW2	Port emergency field wheel.
C1	Starboard main control.
C2	Port main control.

Fig. 12.—Mechanical interlocking of main control and field emergency gear, Q.T.E.V. "Monarch of Bermuda."

fields, which are thus over-excited to give the strong magnetic field necessary for starting the motors. These latter now start to revolve as induction motors. The alternating current in the motor circuit quickly rises to a peak value and, as the motors gain speed, falls to a steady value, when the motors attain a speed corresponding to the speed of the turbines.

The main control wheels are now released from the first sequence catches (by a slight anti-clockwise motion) and are then moved forward to the second sequence catches which again stop further motion. At this point the field contactors of the motors close, which apply 220 volts direct current to the motor fields. The motors thereupon pull into synchronism, which fact is indicated by a fall in the value of the main current. The second sequence catch is then passed, in a similar manner to the first one, and at the end of the second half revolution of the control wheels C1, &c., the booster fields are closed and the booster voltages build up in opposition to the 220 volts direct-current supply, thus reducing the alternator fields to normal excitation.

The main control wheels have now made each one complete revolution, during the first half of which the turbine speed was increased from $\frac{1}{12}$ to $\frac{1}{5}$ value and held constant at $\frac{1}{5}$ during the second half revolution. The wheels C1, &c. can now be moved forward a second complete revolution, which has the effect of altering the governor gear of the turbine so that full speed is attained; during the whole process, of course, the turbine is under the control of the governor as regards its speed.

Full ahead to stop is carried into effect by turning the control wheels C1, &c., back through two revolutions to the stop position, when the process is the reverse of that set forth in previous paragraphs. The sequence catches are not operative when moving the wheels anti-clockwise. It must be remembered that all switching of the main contactors is done "dead," *i.e.*, with the field circuits broken.

To change from full ahead to full astern, the wheels C1, &c., are returned through two revolutions to stop. The direction switches DW1 and DW2 are thrown to astern and the operations are then repeated as described for full ahead.

For alternative running with two inboard motors on one alternator and two outboard motors on the other alternator the connections are changed by means of the isolators IM1, IM2, IM3 and IM4, fig. 10. This can only be done when both the control wheels C1 and C2 are at stop. The operation of wheel C1 will now control the two outboard motors, and wheel C2 will control the two inboard motors exactly as before. All necessary changes of connections are made automatically.

For running all four motors from one alternator, the necessary connections are made by the isolators IM1, IM2, IM3 and IM4, which can again only be done when C1 and C2 are both off. If the starboard alternator is to be used, the operation of the isolators necessary to arrange this has the effect of automatically altering all the other connections, so that wheel C1 now controls all motors and everything now goes on as before. In addition, speed limit solenoids automatically come into action which limit the speed to about 70 per cent, so that the one turbine in use in not overloaded. This limitation of speed comes into action in all cases when one turbine only is being used, *e.g.*, when working with two motors only from one turbo generator.

In the event of the failure of the electrical operation, full control can be exercised by the mechanical emergency gear, which will be understood by reference to fig. 12. It will be seen the direction contactors are provided with emergency direction control wheels HE1 and HE2. These cannot be moved unless one or both (according to running conditions) main control wheels C1 and C2 are in the stop position. When the latter are in the stop position, the interlock levers IL1 and/or IL2 can be thrown down. This allows the direction contactors to be moved (by HE1 or HE2) as required. When this has been done, the interlock lever is returned to normal, which locks the direction contactors and unlocks the control wheel or wheels C1 and C2.

The field contactors can now be operated by the emergency field control wheels EFW1 and EFW2. It will be seen there are four field contactors, each for the starboard and port side, respectively, *i.e.*, for one alternator, two motors and one booster. These emergency field control wheels, however, can only be moved when the main control wheels C1 or C2 are in some position between stop and $\frac{1}{5}$ speed. The wheels EFW1 and EFW2 are provided with sequence catches, as are the wheels C1 and C2. A second swinging interlock bar is provided, which prevents C1 being returned quite to its stop position, unless EFW1 has been returned to "off," thus preventing any change of position of the direction contactors, either electrically or mechanically, unless the fields of all machines have been opened.

Complete electrical and mechanical interlocking is provided, but it is only possible here to give a rough idea of some specially interesting points on this.

The mechanical interlocks include the following in addition to those already described :—

(*a*) Between the ahead and astern direction contactors preventing both closing at the same time.

(*b*) Between the control wheels C1 and C2, and all the motor isolators IM1, IM2, &c., and the alternator isolators IA1, &c.

The latter interlock (*b*) is effected by the levers IL1 and IL2. Movement of IL1, for example, rotates the two horizontal shafts shown, which, it will be seen, are connected together by bell cranks. These shafts carry additional discs (not shown in the

figure) which engage in other discs on the motor and alternator isolators (similarly to those shown in the figure for the emergency direction control wheel). With lever IL1 in the upward position, none of the four handwheels controlling these items on the starboard side can be moved. They are free to move, however, with IL1 in the downward position. But IL1 (and correspondingly IL2) can only be put downwards when C1 is at stop, and pulling IL1 down locks C1 at stop. Hence the motor and alternator isolators can only be moved when C1 is at stop.

Under normal running conditions the starboard and port mechanical interlocks are independent of one another. Should it be desired to work with one of the alternative systems of running (*e.g.*, the two inboard motors from one alternator and the two outboard ones from the other) it is necessary that the mechanical interlocks should be coupled and act as one. This is effected by the lever L. Attached to this lever L is a series of bell crank mechanisms (not shown) engaging with cams on the four motor isolators. With lever L in the uncoupled position, it is impossible for starboard motors to be connected to port alternator, while the latter is in service, and similarly port motors are prevented from being connected to the starboard alternator. These latter interconnections can only be made when the lever L is locking the two mechanical interlocks together.

The two levers IL1 and IL2 are further interlocked with the door of the control cubicle on the Castell key system. This system uses keys having numbers embodied on them. Thus only keys and locks having the same number work together. To obtain possession of the cubicle door key, both levers IL1 and IL2 have to be put in their downward position (thus locking both main control wheels at stop). The key may then be turned (which locks IL1 and IL2 in their downward position), then withdrawn and inserted into a socket on the door framework of the high tension cubicle. Turning the key in this trips out the circuit breakers controlling the excitation of the propulsion system, which cannot be closed again until the key is turned back.

The action of turning the key in this socket releases the actual cubicle door key, which can then be turned to unlock the door, thereby trapping the first key which cannot be turned back. After the cubicle door has been unlocked, the second key can be removed, and if kept in the possession of the engineer while inside the cubicle, effectively prevents anything being made alive again during inspection and repair work.

TURBINE ELECTRIC DRIVE USING INDUCTION MOTORS.

One of the reasons that have caused the asynchronous induction motor to be used in turbo-electric propulsion applications is the possibility of varying the economical speed of the propeller motors with constant electrical frequency, *i.e.*, constant engine speed, by varying the number of poles on the motor. This is simply a question of alteration of electrical connections carried out by suitable switches. As the number of revolutions per minute of the turbine is not altered, an economical slow cruising speed is attained. This was the reason for the adoption of the two speed induction motors for the propulsion of the capital ships of the American Navy. It may be doubted, however, whether it was sound to design a warship upon peace-time considerations. The test of a battleship is the last fraction of a knot and fighting efficiency in battle. However this may be, the application of the induction motor in commercial marine propulsion has been for moderate-sized vessels. In these it allows a particularly high economy to be attained in suitable cases by utilising the main supply of electric power for the auxiliaries as well as the main propulsion.

In the ordinary steamship using steam auxiliaries, any attempt to attain a heat balance, as in a land power station, is well nigh impossible. In such a ship the steam used in auxiliaries varies, depending on the load, from 25 per cent to 50 per cent of the total steam produced. It is obvious that if the power for the auxiliaries be taken from the main electric generators, great economy can be attained. To do this, however, it is clear that the turbine speed must not vary a great deal. In such cases, only a limited range of propeller speed control is obtained by turbine speed control. The propeller induction motors are provided with slip rings, and slower speeds are obtained by inserting a variable resistance across these. This in itself is, of course, very inefficient. As these slow speeds are only required when in harbour and the like, the net loss over the voyage is negligible. The alternating-current motors for the auxiliaries must be arranged, of course, to give their output at the minimum turbine speeds. Such induction motor propulsion schemes have been used in self-unloading ore-carriers on the Great Lakes, which require a large power for the unloading machinery. The arrangement allows the vessels to be slightly manœuvred without stopping the unloading.

A variation of the foregoing, allowing larger variations in the propeller speed while under way, is the use of a three-unit set for providing auxiliary power. This consists of an alternating-current motor, a direct-current generator, and a relatively small steam turbine, all in tandem. When the ship is travelling at top speeds the alternating-current motor, taking its current from the main generators of course, drives the direct-current generator which supplies the auxiliaries while the turbine runs idle. At three-quarter maximum speed, steam is automatically admitted to the turbine which then drives both the direct-current dynamo and the alternating-current machine.

The voltage is regulated on the direct-current machine by an automatic voltage regulator.

A further reason for the adoption of the wound slip ring induction motor for these merchant ships, which take their auxiliary electric power supply from the main power units, is that it is necessary to be able to connect in the propeller motors without a great reduction in speed of the turbines. This can be done with this type of motor by connecting a variable starting resistance across its slip rings. This, of course, would not be possible with a synchronous induction motor, and for this reason, the wound slip ring induction motor must be used in this type of merchant ship having turbo electric propulsion. It may be added, however, that the development of the Diesel-electric drive will most probably prevent any considerable extension of the turbo electric system for medium-sized vessels in the future.

With Diesel engines there is generally no difficulty with regard to auxiliary power, as this can be provided by an auxiliary dynamo driven in tandem with the main generator by the Diesel engine. These remarks apply when the Diesel engine runs at constant speed, as is the case when direct current propulsion motors are used.

DIESEL-ELECTRIC PROPULSION EMPLOYING ALTERNATING CURRENT.

The majority of Diesel electric propelled ships employ direct-current electric machinery. This is discussed later on in this paper. For moderate sizes, such an arrangement is satisfactory, but with large powers, the large current commutators of direct-current generators and motors present problems. Moreover, with direct current it is not possible to increase the working voltage to any great extent so that the currents employed become excessive as the power of the ship increases. The difficulty with using alternating-current generators, having Diesel engines, for large ships is that, from consideration of engine design, a number of prime movers is necessary and it has been considered that the synchronising and running in parallel of a number of alternating-current generators would be impossible under marine conditions. The chief point about this is the initial synchronising of the alternators. Once in synchronism there is no difficulty in holding the machines in step. Brown, Boveri (Patent No. 6848/32) propose to surmount this difficulty of synchronising as follows. The incoming generator is run up to idle speed which is somewhat above the running speed ; the whole plant is then deprived of excitation, and the incoming generator switch closed on to the busbars ; on the excitation switches being re-closed (generally at a point on the regulator to give over-excitation) all the machines are pulled into synchronism and share the load equally. In this way the speed of the ship may be increased by successively switching in additional generators, intermediate speeds between steps being obtained by regulating the governors of all paralleled machines equally.

The scheme is illustrated in fig. 13, which shows the horse-power—propeller-speed characteristic of a single screw ship with three Diesel engines. It will be seen at low speeds one alternator is used running at about half speed. For higher speeds, two or three alternators are used. Either a synchronous motor, of the type illustrated in fig. 5, or an induction motor, can be used. For reversing at full speed ahead, the speed of the Diesels is reduced to approximately 40 per cent by the governors, the excitation cut off, the motor direction switch reversed, and momentarily increased excitation applied. It will be seen that the process of reversing is the same as described above for turbo-generator and synchronous motor propulsion equipments.

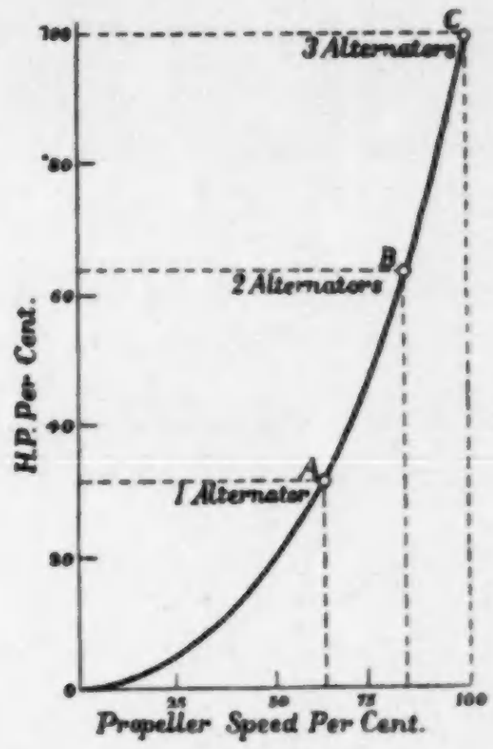


Fig. 13.—Speed characteristics with three Diesel engines.

The only difference is that it is done with the several alternators in parallel. It is to be assumed that in the case of twin-screw vessels there would be a group of engines for each screw, as there would be no object in running the complete installation in parallel. This system has not as yet been applied in practice. A workshop demonstration has been made using six 150-h.p. Diesel engines with a single 815 b.h.p. induction motor loaded to imitate a propeller drive. Tests showed that a complete reversal took place in 14 to 15 seconds, the current in the motor rising to about 2.8 times full load and a reversing torque of 138 per cent of full load torque being exerted. The novelty about this scheme is the use of alternators in parallel, but to drive two synchronous motors from a single alternator is commonplace in marine propulsion. It is somewhat remarkable that the reverse of this has not been proposed before. There can be little doubt that the scheme will have useful applications in the future.

ELECTRIC PROPULSION USING DIRECT CURRENT.

Direct current motors are only suitable for propulsion purposes for small vessels not exceeding, say, 3,000 shaft horse-power. If even as high a voltage as 1,500 volts be used, the current at this horse-power is about 1,500 amperes, and the commutation difficulty and that of the size of cables set this limit. Turbines for these small powers would nowadays hardly be considered, so that the only comparison necessary to be made is that of the Diesel-electric ship versus the motorship. As two engines must generally be used, it follows that on a motorship two screws are necessary against one on the Diesel-electric, as with the latter drive the two electric motors can be mounted on the one shaft. Moreover, with the electric system the speed of the propeller can be slow and thus more efficient. These considerations, together, can more than compensate for the electric losses. There are other incidental advantages of the electric system; easier starting is obtained and there is no necessity for reversing the engine.

SELF-LOADING SHIPS.

The electric system permits the economical design of ships which require an amount of power in dock for loading and unloading comparable in amount to that required to propel them. An illustration of this is the *E.M.V. Cementkarrier*. This vessel is used for the carriage of cement on the Canadian Great Lakes, and is loaded and unloaded entirely by electrically-driven machinery consisting of cement pumps and scrapers. For unloading, the cement falls by gravity through hoppers to tunnels in the bottom of the ship. By means of steel cables the scrapers are hauled fore and aft, bringing the cement to the pumps and air compressors, which discharge it to the dock side. It would clearly be economically unsound to provide the electric generators only for use in the docks, so that it may be said that electric propulsion is necessary if such labour-saving vessels are to be constructed.

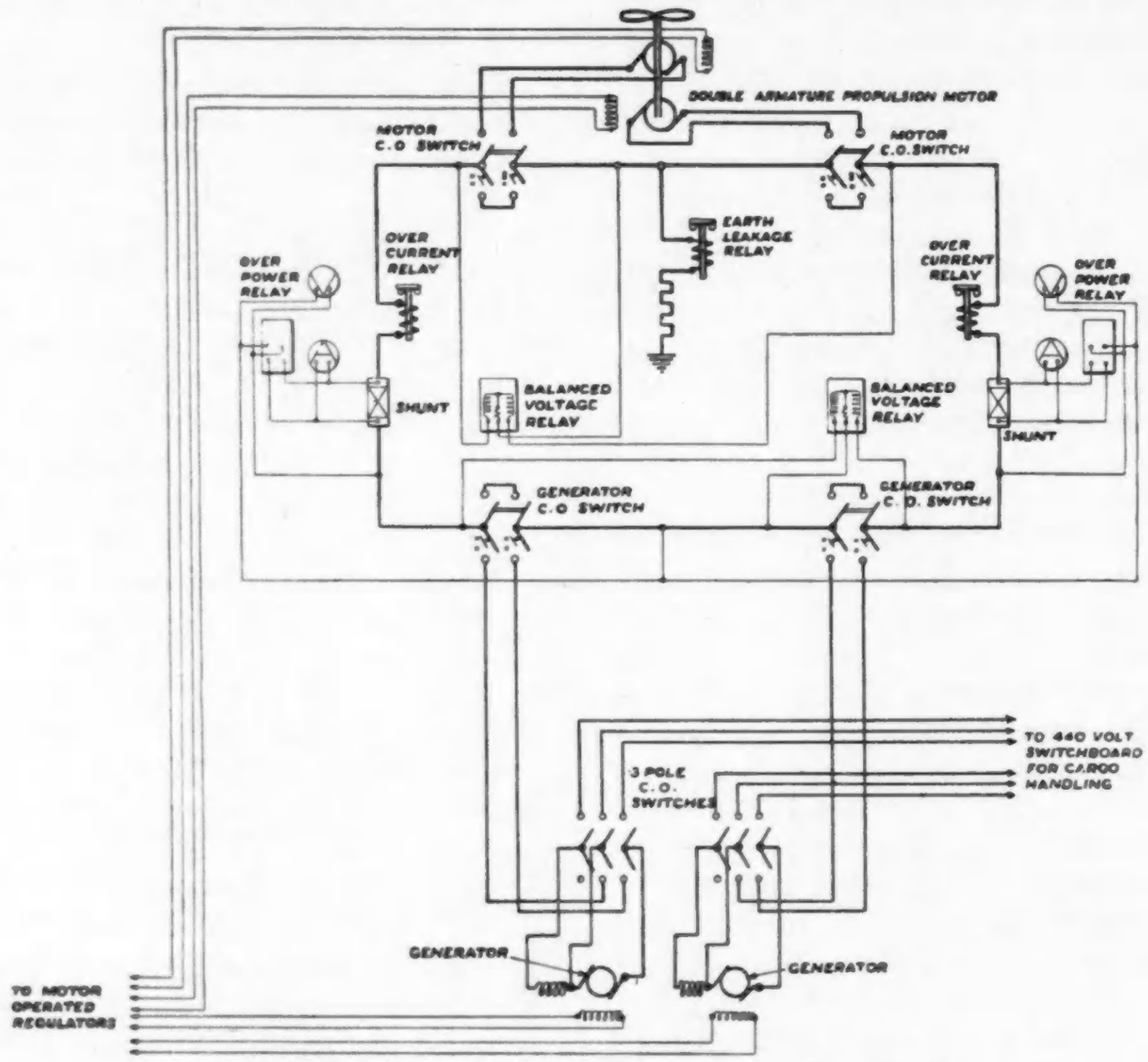


Fig. 14.—Schematic diagram of main propulsion circuits; E.M.V. "Cementkarrier."

The efficiency of the cargo-handling plant may be gauged by the fact that the total capacity of the hold, viz., 2,300 tons of cement, can be discharged in four hours, requiring the services of only two or three men. Automatic electric mooring winches are provided to haul in as the vessel rises in the water with the discharge. The unloading requires the following machinery:—two 208 h.p. motors for the air compressors, a 300-h.p. motor for the screw pump, two 100-h.p. motors for the scraper winches, and four 18-h.p. automatic winch motors.

ELECTRICAL EQUIPMENT OF E.M.V. "CEMENTKARRIER."

This vessel has a total deadweight of about 3,150 tons, and is driven by two 360-kW Diesel direct-

current generators of 500 h.p., running at 220 r.p.m., and a double armature propulsion motor of 775 h.p., running at 100 r.p.m., directly coupled to the propeller shaft. The engine-room auxiliary load is provided by 50-kW generators coupled in tandem one each to the main generators. The cargo handling machinery demands, on occasion, a larger amount of power than the propulsion power. Fig. 14 shows the schematic diagram of the main propulsion circuits. Under normal conditions, the two shunt excited generators and two motor armatures are all in series. It will be seen that the three-pole change-over switches at the bottom of the diagram connect the generators either to the propulsion or cargo handling circuits at will ; in addition, two-pole change-over switches are supplied to cut out any of the four machines in the event of a fault. Reference to the diagram in fig. 14 will show that the mid-point of the motor windings is connected to earth so that the maximum voltage in the circuit to the ship's frame is 440 volts. When handling cargo, the generators are connected as compound machines.

All main circuit switching is carried out with excitation cut off. This is done by means of sequence catches on the motor and generator change-over switches (see fig. 14). The initial movement of these automatically cuts off the corresponding excitation circuit, the delay due to the catch allowing sufficient time for the field flux to die down. The switches are of the make- before break-type, so that the armatures are short-circuited before being entirely cut out of circuit.

If the ship be running with reduced power it is necessary to vary the relative excitations of the generators and motors so that the propeller speed be limited to an extent corresponding to the power available. This is done simply by the provision of auxiliary contacts on the various field contactors which, on operation of the latter, insert and cut out the resistances necessary in the various field circuits. Thus the necessary change in field strengths are brought about automatically.

Balancing relays operate should the voltages of the two generators or the two halves of the motor vary due to a fault. Operation of the balancing relays cuts off the field of the faulty machine which, in turn, as stated above, automatically makes the necessary changes in the other field circuits to suit the new running conditions. Earth leakage faults and persistent overloads shut off the whole of the excitation. After the balanced voltage relays have disconnected the field of a faulty machine, the latter can be cut out of circuit without interruption of the supply, as the changeover switches are of the make- before break-type.

As with most direct current ship propulsion, speed control is on the Ward Leonard system. The possibility of the use of this system which is afforded by direct current is, in fact, one of the chief advantages of the latter. The principle is very simple. With a shunt motor having constant excitation, the speed of the motor is proportional to the voltage applied to its armature. Thus, by simply varying the excitation of the generator, any motor speed from

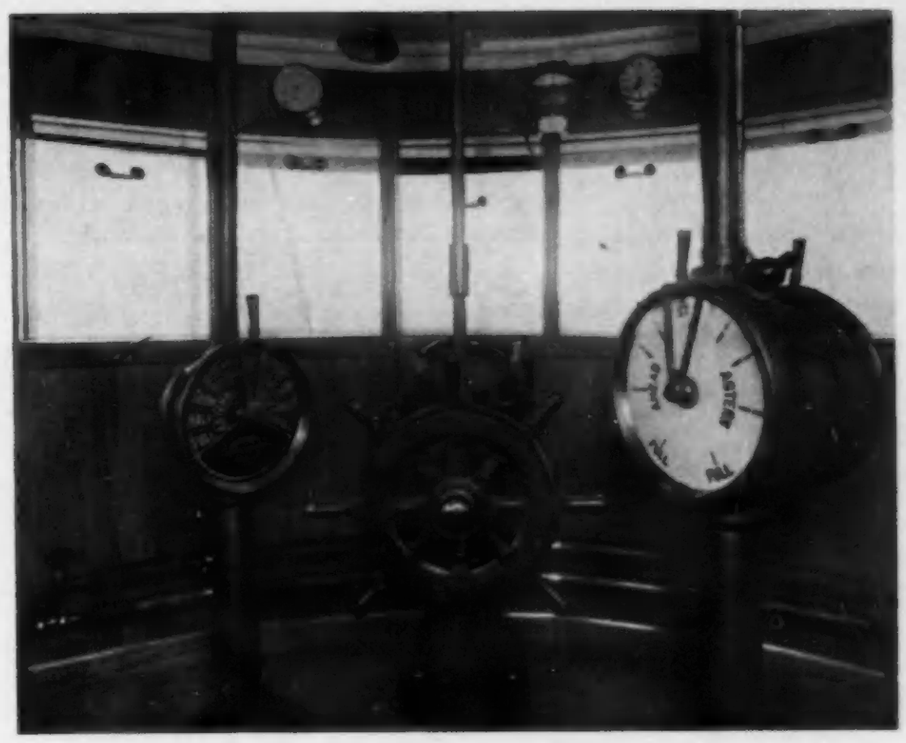


Fig. 15.—Interior of wheelhouse, E.M.V. "Cementkarrier."

zero upwards can be obtained. Reversal of the generator field is followed by reversal of direction of rotation of the motor. Fundamentally, therefore, all one has to do is to vary and reverse the field of the generator to obtain full speed control of the motor.

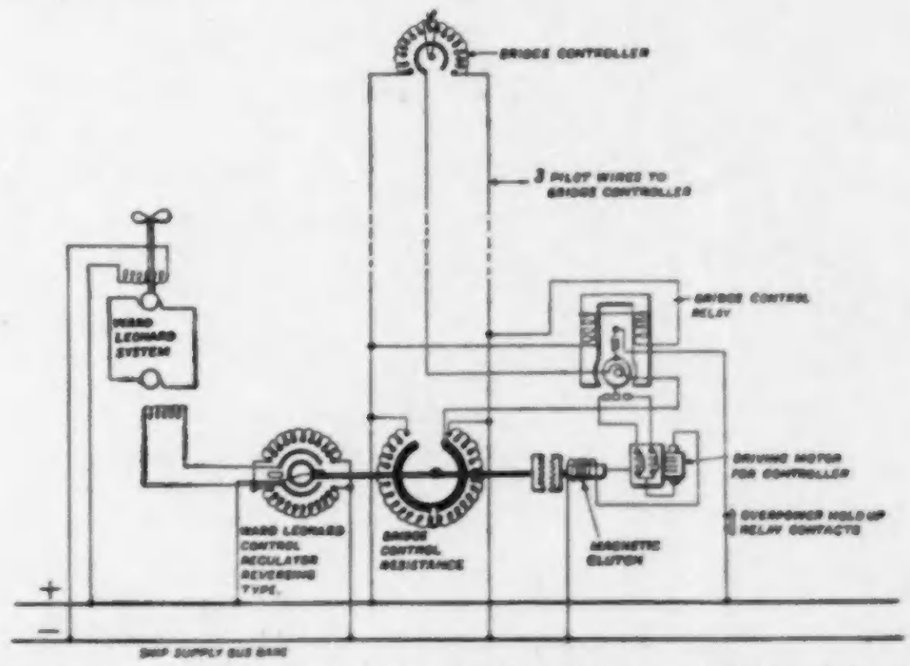


Fig. 16.—Schematic diagram of bridge control for Ward Leonard propulsion gear ; E.M.V. "Cementkarrier."

The scheme is, therefore perfect for bridge control. Fig. 15 shows the interior of the wheel-house in the *Cementkarrier*. To the left of the wheel is the ordinary telegraph for use in emergency. Normally, full-speed control and reversing is performed by moving the handle of the controller on the right. As this handle is moved, the revolutions per minute of the propeller are seen to vary on the indicator placed on the left of the clock. Actually, on the *Cementkarrier*, three control stations are provided,

in the wheel-house, on the flying bridge, and in the engine room, in addition to manual control in the engine room.

The movement of the arm of the controller in the wheel-house moves a contact over the studs of a resistance connected across the 220-volt battery. A similar resistance is mounted on the main generator field regulator. It will be seen (fig. 16), that if both arms are in corresponding position, no current passes through the relay which is connected between

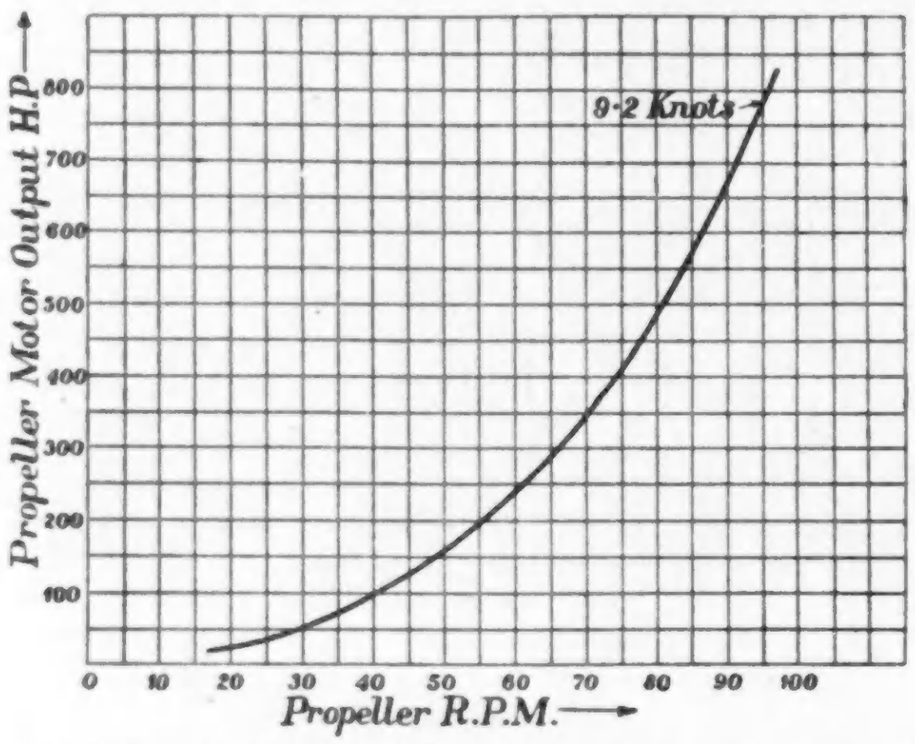


Fig. 17.—Relationship between propeller motor output and propeller speed; E.M.V. "Cementkarrier."

the two arms. Should the bridge arm be moved, current passes in one or the other direction through the relay. The latter closes the circuit of the small ½-h.p. motor which drives the main regulator. The latter is then moved until the arm on the control regulator takes up a position again corresponding to that of the bridge controller, when further motion is arrested. An additional relay operates a clutch which disengages the ½-h.p. motor when current ceases to flow through the relay; overshooting is thus prevented. It will be seen that only three wires are necessary to the bridge control.

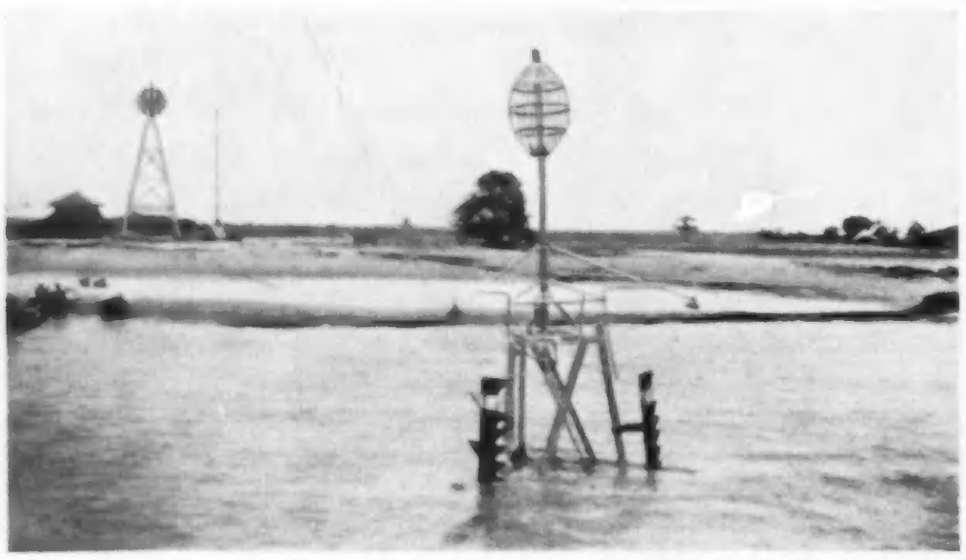
In the circuit of the rheostat-operating motor are connected the contacts of the over-power relays shown in fig. 14. Should too much power pass between the generator and propeller motor due to too rapid acceleration or overspeed during deceleration owing to motoring of the main generator, the relays stop the rheostat-driving motor until the overload has decreased and the relays reset.

The trial results are given in fig. 17. Under bridge control, the time taken to reverse the motors from full speed ahead to full speed astern was approximately 16 seconds. As regards the balanced voltage protection on shutting down one engine, when this had fallen about 15 per cent. in speed, the field contactor tripped, and the ship settled down to reduced speed on one generator with hardly any perceptible disturbance. The usual voyage of the *Cementkarrier* is between Montreal and Lake Erie, and includes some six canals and 46 locks. The extreme ease of control, allowing way to be immediately checked on entering the locks, has proved the system of propulsion and control adopted to be eminently suitable for the service.

The *Lockfyne*,* which works on the West Coast of Scotland service, is another example of bridge control. It is a twin-screw vessel with Diesel-electric propulsion, having two direct-current generators driven by Diesel engines, each of 1,000 indicated horse-power and two 670 b.h.p. 438 r.p.m. motors. Actually, two bridge controllers are used, one each side of the bridge and coupled together. Contactors operated by cams are located in the base of the controller. These make the necessary connections for reversing and obtaining six speeds from one-quarter to full speed. Intermediate speeds are obtained by regulator control in the engine room. There are two handles on each controller, one being for the port motor and the other for the starboard motor. The arrangement requires a much larger number of control wires from the bridge to the engine room than does the scheme illustrated in fig. 16.

* See ENGINEERING, vol. cxxxi, page 730 (1931).

Tide Gauge and Beacon Light on Rangoon River.



An electrically lighted tide-gauge and beacon light have recently been erected at Elephant Point near the mouth of the Rangoon River, about 25 miles from Rangoon. The installation consists of an 800-watt electric lighting set installed inside the beacon tower (seen in the background) which supplies current for a 250-watt Osram tubular projection lamp in the beacon and two 200-watt Osram lamps mounted on the tide-gauge (in the foreground). The beacon tower is mounted on rails and can be moved bodily according to the height of the river.

The Witton High Frequency Electric Melting Furnace.

(Stobie System).

By VERDON O. CUTTS,
Industrial Heating Dept., of The General Electric Co., Ltd.

In the May issue of the G.E.C. Journal was published a short article in which the author outlined the advantages of the high frequency induction furnace for melting steel and ferro-magnetic alloys. A full description of the new Witton high frequency furnace is given in the present article.

COLLABORATION between representatives of different branches of science invariably proves of benefit to all. In no instance is this fact more evident than in the field of electro-metallurgy. The close co-operation of the electrical engineer with the metallurgist has rendered possible industrial achievements which were previously unattainable. The development and application of the high frequency induction electric furnace is one of the most recent examples of this and probably the most important, and has enabled steel and other alloys to be produced economically and under improved workshop conditions, having a purity and precision of composition which cannot be obtained with any other type of furnace.

BASIC PRINCIPLES.

It is well known that if a piece of steel, or other metal, be placed within a coil of wire, through which an alternating current is passing, the alternating magnetic field produced by the current produces an electric current in the piece of steel, which becomes heated. The heat produced varies as the square of the current. The strength of the induced current depends, other factors being equal, on the strength of the magnetic field which passes through the steel and, to a lesser extent, on the periodicity of its alternations. The magnetic field depends, again assuming other factors are equal, on the ampere turns per unit length of the inductor coil. Thus, for a given size of inductor and a given metal charge, the temperature that the charge will gain can be determined with precision by measuring the high frequency current through the inductor.

This describes in the simplest possible manner the basic principles of high frequency induction heating. Other considerations, such as the depth of penetration of an alternating magnetic flux into a metallic charge, are the intimate concern of the designer rather than the user, and do not affect the broad principles outlined in this general statement.

DEVELOPMENT.

Older and well-known types of high frequency furnaces are of the coreless type and represent a natural transition from the well-known, low- and normal-frequency, core-type, induction furnaces. When the iron core was dispensed with for practical and metallurgical reasons, it was found necessary, in order to obtain a secondary current of sufficient value to melt a body of metal, to increase the frequency of the current in the primary coil. Such furnaces (see fig. 1) consist essentially of an inductor coil, which is a helix of water-cooled copper tubing, with a crucible containing the metal charge which forms the secondary. They have proved of great value to the steel and some non-ferrous industries because they have presented to the metallurgist a melting unit capable of attaining any temperature within the practicable range of available refractories without any possibility of contamination of the charge by carbon, sulphur or other deleterious elements. Invaluable though their use has undoubtedly been, a critical examination suggested the possibility of substantial improvements being made. It was realised that with the removal of the iron core, the conductivity for magnetic flux had been reduced to the magnetic conductivity of air with the corresponding reduction of flux. Also, the fact that the magnetic field was uncontrolled as regards its distribution, pointed to the presence of stray magnetic fields which not only had the effect of limiting the efficiency of the furnace but made it imperative that no magnetic material should be used in the construction of the furnace. This, obviously, accounted for the use of asbestos cement and even wood for the furnace casing and for the fact that the inductor coil could not be more adequately supported externally to withstand the pressure of the charge from within. Subsequently, a structural steel body or casing was adopted for the coreless type furnace, a magnetic shield of sheet copper being introduced to prevent overheating of the furnace

casing by the stray fields. This, however, was only a palliative. The problem still remained how to make the transition from the old and well-known, low- or normal-frequency, core type, induction

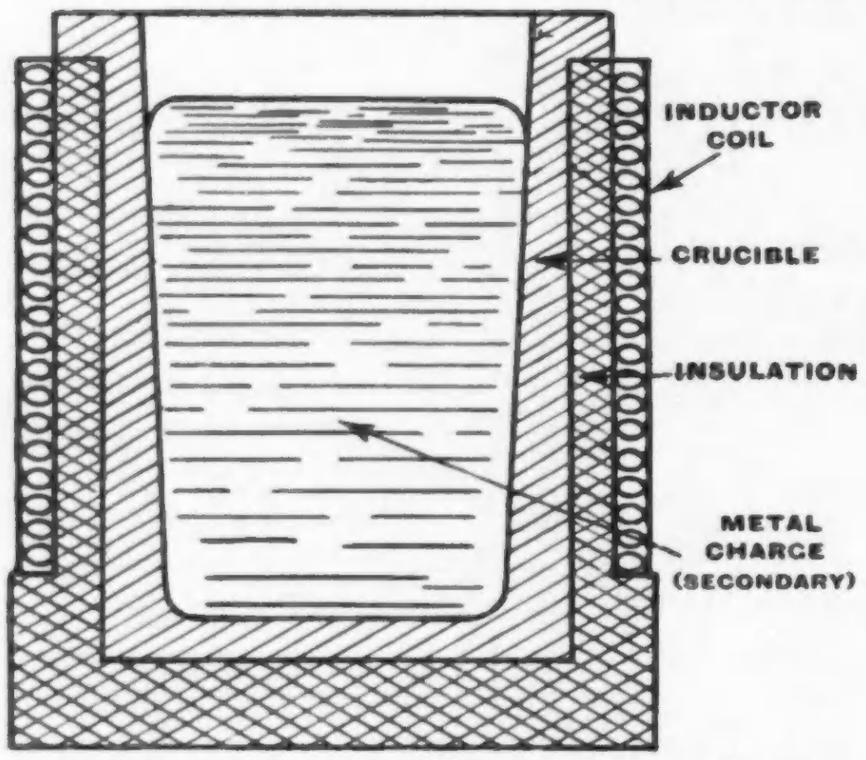


Fig. 1.—Coreless type of high frequency furnace.

furnace to the high frequency furnace, without incurring these disabilities.

THE WITTON HIGH FREQUENCY FURNACE (Stobie Patents).

The solution was found to lie in a furnace of the partially-cored type invented and developed by Mr. Victor Stobie and produced by the G.E.C. as the Witton high frequency induction furnace. In this furnace that portion of the magnetic field not passing through the charge passes through thin laminations of special alloy steel having a conductivity for magnetic flux which is several thousand times

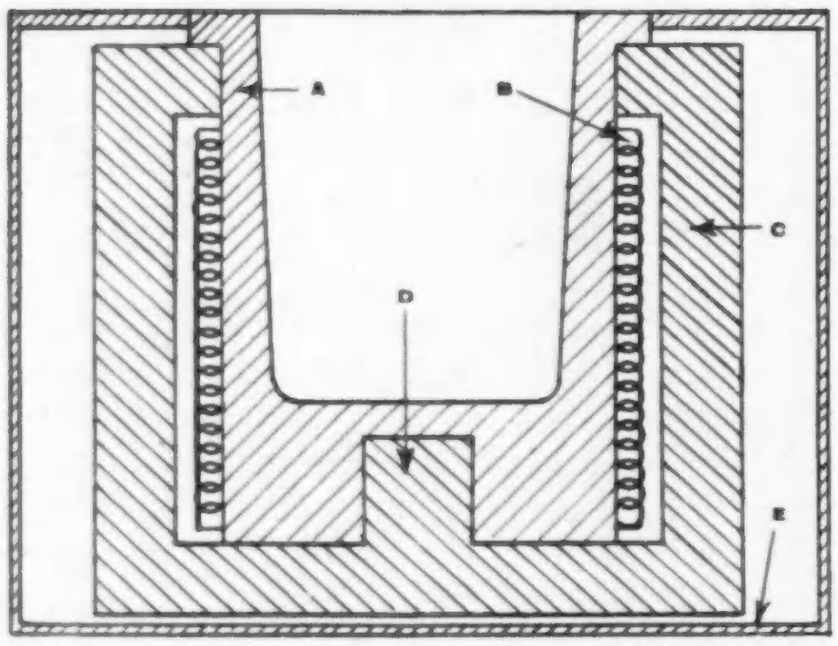


Fig. 2.—Cross section of the Witton high frequency furnace.

that of the air path in furnaces of the coreless type. This alloy steel path "C," fig. 2, is brought to the nucleus of a core "D," fig. 2, in a central position below the crucible, "A," and in line with the vertical axis of the inductor coil, "B." The electro-magnetic system furnishes an intensely strong and centrally situated magnetic field within the crucible containing the charge, and results in obvious and valuable economies. It will be evident that the provision of this ferro-magnetic path or partial coring has the additional effect of reducing the stray magnetic field to an imperceptible amount and has an important influence on the general construction of the furnace. The furnace body is of substantial iron and steel construction which will withstand the rough usage of the workshop, while the massive alloy steel container forms a rigid support for the internal crucible and the inductor coil and for the external body. Since mention has already been made of the use in some coreless furnaces of sheet copper shields in an attempt to prevent overheating of the furnace casing by stray fields, it should perhaps be pointed out here that, since such a field cannot terminate in a core entering the vertical axis of the inductor coil or furnace, the presence of the stray field must tend towards decreased efficiency.

CONSTRUCTION.

The Witton high frequency furnace consists essentially of :—

1. A crucible, built up of shaped bricks or made by ramming refractory material into shape in the furnace.
2. A spiral copper inductor coil surrounding the crucible and carrying the high frequency current.
3. A high magnetic, alloy steel container which supports the inductor coil and the crucible.
4. A metal casing surrounding all the above and forming the exterior of the furnace body.

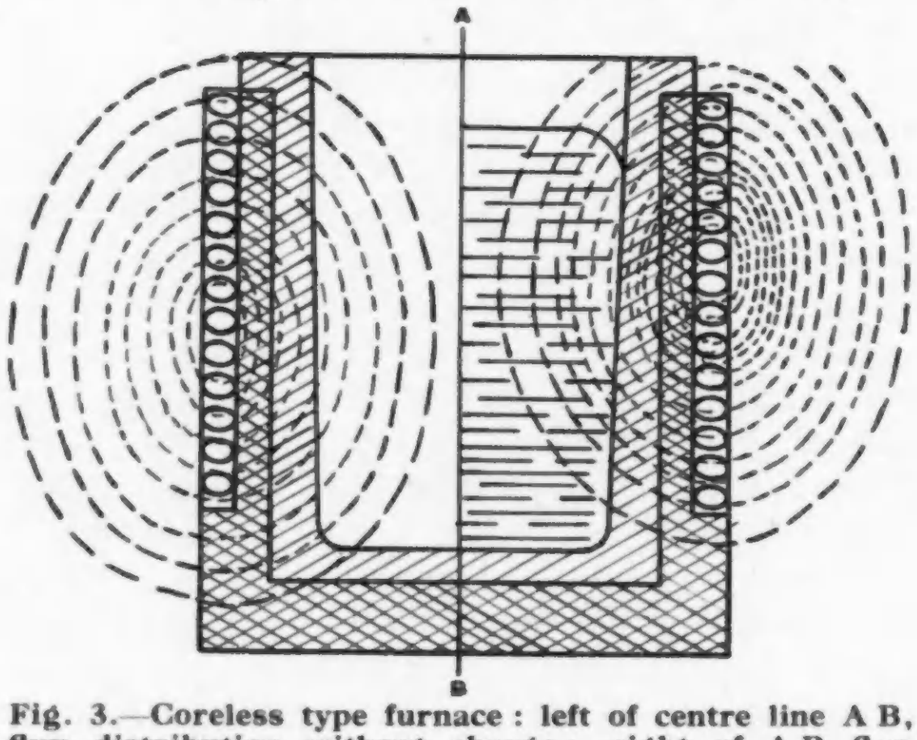


Fig. 3.—Coreless type furnace : left of centre line A B, flux distribution without charge ; right of A B, flux with charge.

A cross section of the furnace is given in fig. 2. This shows diagrammatically the electrical system and illustrates the strength of construction which this system renders possible.

The water-cooled inductor coil "B" is insulated and fits against the alloy-steel container "C." No

heat from the crucible or current from the inductor coil can reach the container. Actually, the container is earthed, giving adequate protection even were the insulation of the inductor coil to fail, or the molten metal charge to find its way through such a stoutly reinforced crucible. The crucible is built either of acid or basic brickwork, or is rammed into shape against the inductor coil. The furnace body "E" is bolted to the alloy steel container. The strength of the magnetic field within the crucible of the Witton furnace having been increased by the provision of the ferro-magnetic path already referred to, it has been possible to reduce the periodicity of the high frequency current employed and to increase its voltage. Both these modifications are desirable and have the effect of reducing losses; the one by reducing eddy-current and hysteresis losses and the other by reducing I^2R losses. The power factor of the furnace is also improved owing to the use of a lower periodicity and smaller current and, with improved power factor, less condenser capacity is necessary and smaller inductor, smaller cables, etc., can be employed with proportionately reduced losses in respect of these items.

It is interesting to note the effect which the alloy-steel container and core nucleus of the Witton furnace have on the magnetic flux distribution within the furnace. This is illustrated diagrammatically in figs. 3 and 4. It is well known that a current induced in metal by an inductor coil does not, normally, spread itself uniformly across the whole section of the metal. It penetrates only a certain depth from the furnace, the depth depending, among other factors, on the periodicity of the induced current; the lower the periodicity, the greater the penetration. At frequencies used in high frequency furnaces melting a metal such as steel, the penetration tends to be shallow; a wide crucible of steel scrap within a coreless furnace is heated mainly near the inner diameter of the crucible. The new furnace heats the scrap more uniformly as its central core forces a strong magnetic flux to enter the central portion of the crucible and to distribute itself throughout the charge.

The surface of a bath of molten metal in a high frequency induction furnace is convex, the level of the centre part of the surface being higher than that of the sides. This is due mainly to the known phenomenon of inter-repulsion between adjacent conductors carrying electrical current in opposite directions. The current in the furnace charge travels in the opposite direction to the current in the inductor. Actually, the inter-repulsion is between the opposed magnetic fields of the two currents. It has already been shown that the electro-magnetic system of the particular furnace under discussion ensures an intensely powerful flux which, being

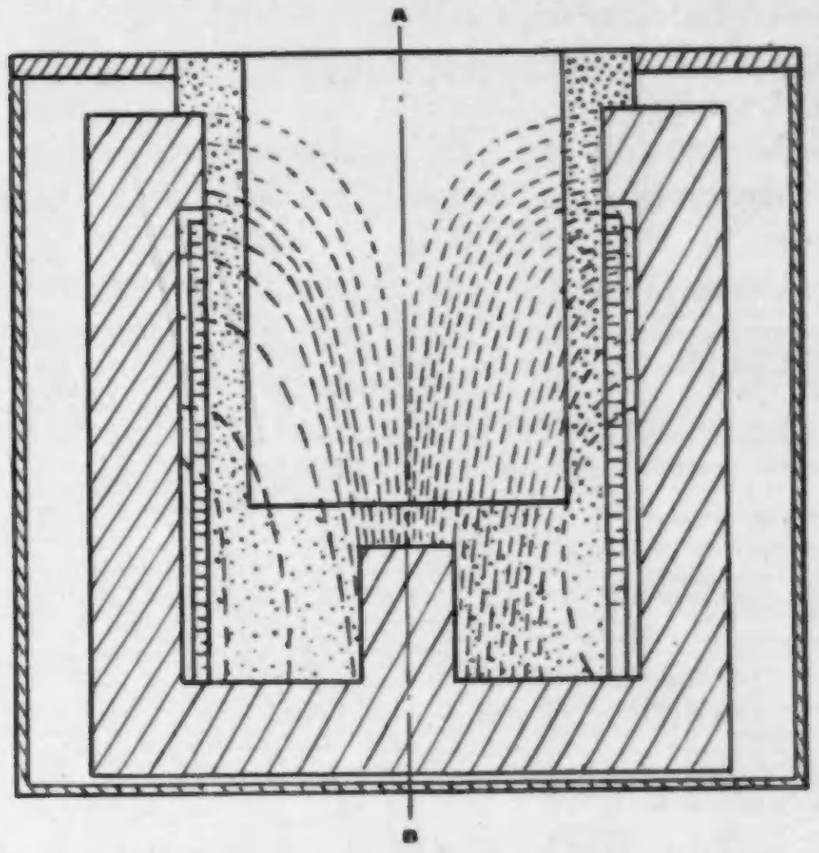


Fig. 4.—Witton furnace: left of A B, flux distribution without charge; right of A B, flux distribution with charge.

centrally placed, repels in a radial outward direction the field of the current it induces in the charge, and tends to push the molten metal up the inner wall of the crucible. By the nature of the total forces, the central axial rise of the metal remains the stronger, but the circumferentially upward force opposes any abnormal central "swell" of the charge. But for this fact, the relatively low periodicity of current which is

Fig. 5.—Witton high frequency furnace installed in the north of England.

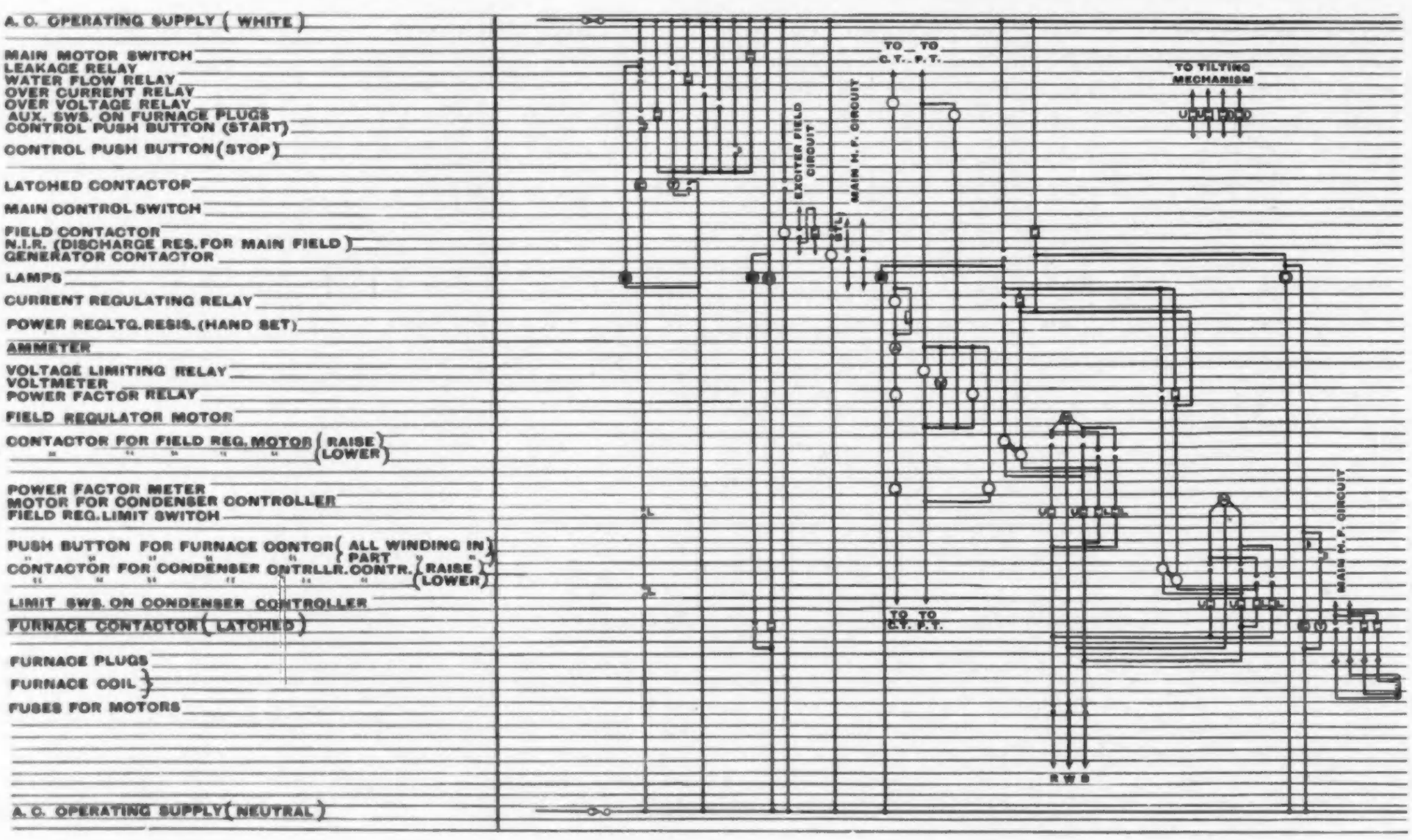
used on the Witton furnace would cause a greater swell on the surface of the bath than is desirable for metallurgical reasons. Another factor which reduces this "swell" in the partially cored furnace is that the design facilitates the use of a reasonably wide crucible;

narrow and deep crucibles tend to increase swell. It will, of course, be apparent that the automatic stirring effect which causes this "swell" is a most desirable feature, as each melt is of uniform composition throughout.

COMPLETE HIGH FREQUENCY ELECTRIC MELTING INSTALLATION.

So far, the technical considerations involved in the design of high frequency furnaces of the coreless and partially cored types, and the effect of providing an alloy steel path of high conductivity for magnetic flux in furnaces of this type have been discussed. It is now proposed to give a brief description of a complete high frequency electric melting installation. This consists essentially of a motor-generator set, condensers, automatic control gear and the furnace itself.

The motor-generator set. A motor-driven single-phase alternator is employed, capable of the desired output at a voltage and periodicity which is appropriate to the particular purpose for which the furnace is to be used. The design of the alternator depends on the size of the set. The motor is usually of the three-phase, slipring induction type. These two machines, with the exciter, are mounted on a combination bedplate forming a self-contained unit.



Contactor or relay operating coil.

Closing and tripping coils respectively on latched type contactor or breaker.

Contact on circuit breaker, contactor or relay, which closes when the operating or closing coil is energised.

Contact on circuit breaker, contactor or relay, which closes when the operating coil is de-energised.

Auxiliary contact, closing with main contacts but fitted with time delay when opening.

Push button switch: push to close circuit.

Red, white and green indicating lamps.

Fuse.

Three-phase motor.

Limit switch: opens when upper limit of travel is reached.

Limit switch: opens when lower limit of travel is reached.

Limit switch: closes when lower limit of travel is reached.

Fig. 6.—Schematic diagram (with key) of Witton high frequency furnace.

Condensers. A bank of condensers is provided for power factor correction so that the maximum capacity of the alternator may be taken at unity power factor.

Automatic Control gear. The automatic control gear usually consists of a stator control cubicle, exciter pedestal, liquid starter, automatic and protective relay panel, push button control cubicle and

power factor control gear, together with the necessary multi-core cables required for interconnections between the control panel, relay panel, etc. This equipment includes switchgear for starting the motor-generator set by hand; all other operations are carried out by push button control from the furnaceman's control panel and by automatic control gear which provides power factor correction and maintenance of any desired power on the furnace.

The Furnace. Sufficient has been written in the earlier part of this article to indicate the general construction of the furnace. It is only necessary to add here that it is tilted by means of an electric motor operating through spur and bevel gear, the axis of the trunnions being in line with the pouring spout. considerations governing the layout are convenience of operation and economy of floor space. In a typical case, the furnace itself is mounted on the front of the furnace platform with the controller for the tilting motor conveniently near. At the back of the platform, the control pillar is mounted against the wall and, nearby, the cooling water control apparatus, water flow relay and waste water sump. Immediately behind all this, in a separate room, well built to keep out dust and dirt, are housed the power unit, the condensers and all the switchgear. Alternatively, the power room may be to the side of the furnace instead of at the back. The motor-generator set and its starter may, if desired, be some distance away from the furnace.

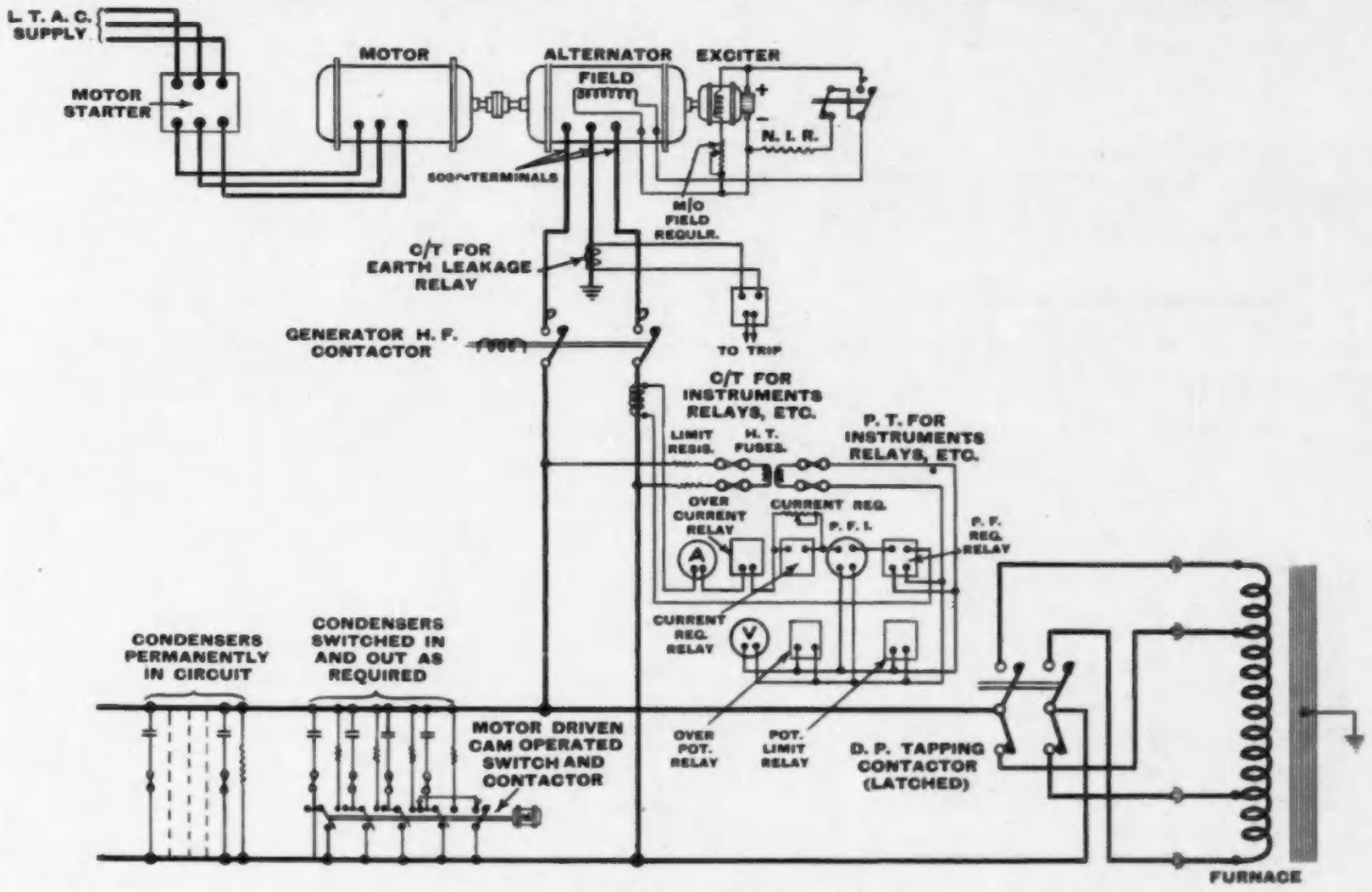


Fig. 7.—Diagram of connections.

AUTOMATIC CONTROL GEAR.

Object of Automatic Control Gear. During the course of a normal run of the furnace, varying conditions in the latter make it necessary continuously to regulate the electrical equipment in order to maintain a constant power input to the furnace whilst maintaining a good power factor on the generator. In this way is the output of the generator kept within the kVA capacity of the unit.

The main object of the automatic gear is so to render the necessary electrical adjustments that the furnaceman can devote his attention to the metallurgical process. Further advantages include a more consistent loading of the plant and a quicker operation of the controls, resulting in an increased output from the furnace.

The general layout of the plant is made to suit the existing site and local conditions. The chief

Description of Operation. The power unit is started from the power room, an indicating lamp on the furnace control board being provided to show that the power unit is ready for service. The cooling water for the furnace coil is then turned on, and the water flow operates the water flow relay and prepares the equipment for starting. The furnace circuit is switched on to the starting section of the furnace coil by depressing the appropriate push button on the furnaceman's switchboard.

The generator main contactor is now electrically closed by operating another push button on the furnaceman's switchboard. Automatically the field contactor closes and the generator becomes excited (field rheostat all in).

The current regulating relay now takes charge and operates the field rheostat to raise the current to the value desired by the furnaceman according to

his prior setting of the power regulating handwheel. The voltage required for this purpose is chosen automatically by the same device.

When the charge is red hot the full current is maintained on a falling voltage. It is then necessary to put the whole of the furnace coil into circuit. To accomplish this, the main generator contactor is tripped by depressing an appropriately labelled push button on the furnaceman's switchboard, when the alternator field contactor will also trip and suppress the alternator field. The push button to change the coil tapping switch is then depressed. The completion of this operation is indicated by lamps on the furnaceman's switchboard. The generator switch is then reclosed, and the current regains the value indicated by the setting of the power-regulating handwheel.

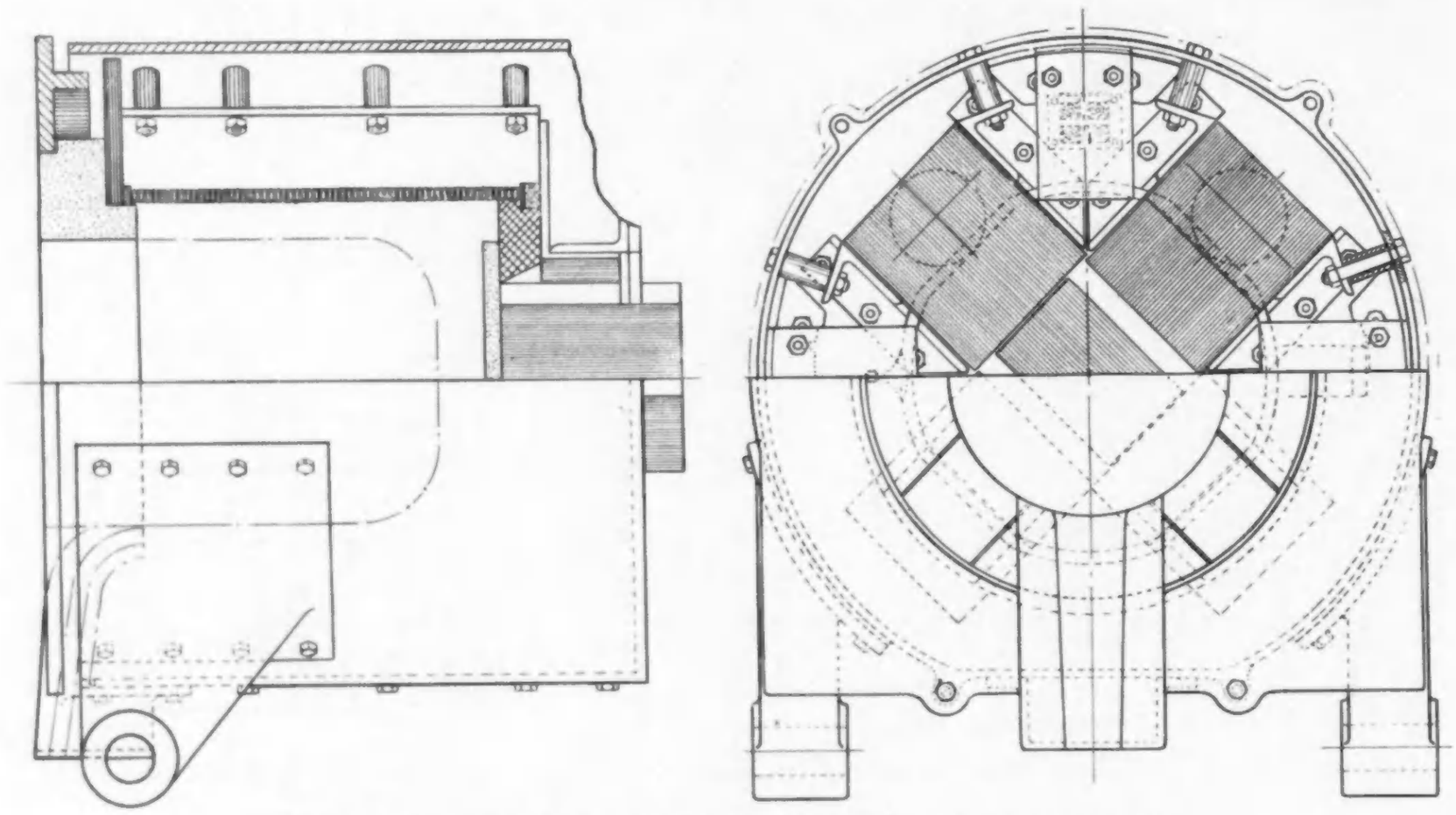


Fig. 8.—General arrangement of Witton high frequency furnace.

At all necessary times a power factor relay automatically operates to switch in or out the condensers necessary to maintain the power factor of the generator circuit at a very high value.

The following protective features are available :—

1. The switchgear is completely interlocked to prevent operating mistakes.
2. Failure of the cooling water supply prevents the generator from being excited or, if the generator is excited when the water fails, the generator and field contactors open and cut off from the furnace.
3. If for any reason the generator becomes seriously overloaded, the generator and field contactors open and cut off the load.
4. If an earth leakage develops on the high frequency circuit the plant shuts down.
5. If a serious over-voltage occurs on the high frequency circuit, the generator and field contactors open and cut off the load.
6. If the motor driving the power unit becomes seriously overloaded the plant shuts down.

In cases 3, 4 and 5, the relays are made to be reset by hand to prevent the plant being re-started from the furnaceman's switchboard.

INDUSTRIAL APPLICATIONS.

By far the largest and most important field of application of the high frequency electric melting furnace is in the iron and steel industry. It also has non-ferrous applications which, though important in themselves, are not nearly so extensive as its uses and potentialities in the ferrous trades. It is, for example, an ideal melting furnace for high grade nickel-chromium and similar alloys. Its principle uses are for melting alloy and carbon tool steels, stainless iron and steel, and other special alloy steels.

Metallurgical advantages. This type of furnace enables steel and other metals to be melted on a commercial scale and under ordinary workshop conditions with a precision which, otherwise, is only obtainable in the laboratory. A furnace charge can be melted without any possibility of picking up impurities. In fact there can be no involuntary change in the composition of a charge within the furnace except for that very slight modification which is due mainly to de-gasification of the charge. The product is identical in composition with the sum of the materials charged into the furnace. Metal so melted cannot take up sulphur as it does in the coke

or producer-gas fired furnace. High chromium and other alloys which have a strong affinity for carbon are melted without carbon increment. Furthermore, steel melted in the Witton high frequency furnace has been found by microscopic analysis to be practically free from non-metallic oxides or slag inclusion. Another important feature is that of temperature control; the casting temperature of a charge can be adjusted with extraordinary precision. It is just as easy to work to any predetermined temperature on a large furnace working under ordinary production conditions as to do so on a small furnace in the laboratory.

A further feature which is of the greatest metallurgical importance, and which is peculiar to the high frequency electric melting furnace, is the automatic stirring action which is caused by electrodynamic forces within the molten charge. This ensures a uniformity of composition throughout each charge, which is not possible in any other type of furnace. An alloy, such as high speed steel, the constituent materials of which vary considerably in specific gravity, is melted under conditions which do not permit of any variation in composition from top to bottom of an ingot, nor between any two ingots from the same charge.

ECONOMIC CONSIDERATIONS.

Normal experience leads one to expect benefits such as those which have just been described to be accompanied by increased costs of production. In this instance the reverse is the case.

Obviously, when considering cost of production in an electric furnace, the first item to be considered is that of current consumption. The current consumption of the high frequency furnace described is lower than that of an arc type furnace. It is also lower than that of other high frequency furnaces for reasons given in the early part of the article. Comparative figures regarding current consumptions are apt to be misleading in an article of this kind because it is impossible to ensure that operating conditions are identical in any two cases which may be chosen for the purpose of comparison. However, as an indication of the current consumption, a run of Nickel-Chromium-Molybdenum stainless steel in a furnace having a nominal capacity of 5 cwts. per charge might be cited. The current consumption for the run worked out at 574 units per ton. Plain carbon steel has been melted from cold to pouring temperature with a current consumption as low as 485 units per ton. This latter figure is not put forward necessarily as a basis for routine commercial calculations, but rather as an indication of the efficiency and economy of the particular furnace under discussion. This feature of low current consumption is, of course, accounted for by the fact that the heat is generated within the charge itself and is not communicated to it from without. Actually, the metal is hotter than the crucible in which it is contained.

Mention of current consumption in connection with the melting of steel will immediately bring to the mind of the practical steel maker the question of electrode consumption. This is not an inconsiderable item in the cost of operating arc furnaces, but is entirely absent from the cost sheet of a high frequency furnace.

Labour costs are reduced to a minimum; little supervision being required other than for charging and pouring. The automatic control system which has already been described is an important factor in this respect.

Maintenance costs are low. The motor-generator, like all modern rotary electrical machinery, has a

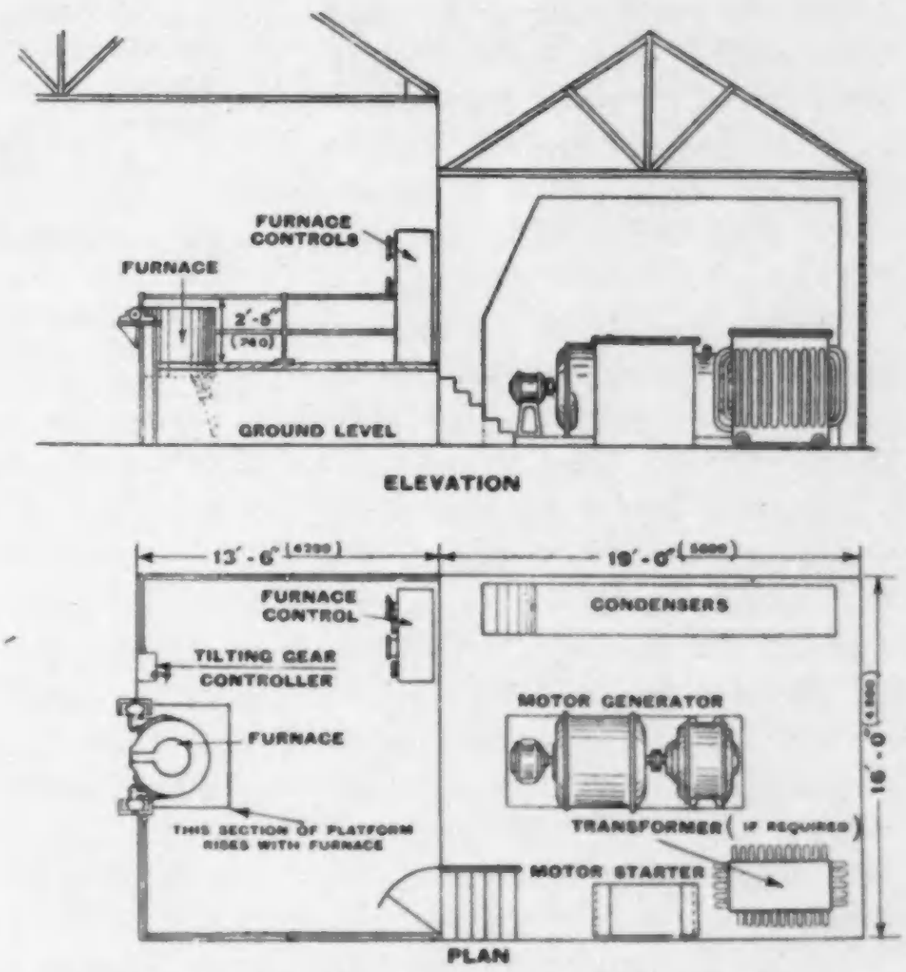


Fig. 9.—Typical layout of complete electric melting furnace equipment.

very long life. The remainder of the installation, with the exception of the furnace itself, is of standard construction and suffers very little depreciation. So far as the furnace is concerned, the only part which needs replacing periodically is the built-in crucible, the life of which depends upon the steel or alloy melted in it. Its replacement is a simple and inexpensive matter.

Two other factors which are of economic importance should, perhaps, be mentioned. The first is that the feature of rapid melting renders a Witton high frequency furnace of small unit capacity capable of a comparatively large output. The second is that the furnace can be used intermittently if desired without incurring the penalty of considerably increased running costs.

High Tension Overhead Transmission Line Fittings.

PART II.

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This is the second part of an article dealing with the design of fittings employed for the suspension of overhead transmission lines and earth conductors. The first part appeared in the G.E.C. Journal, Vol. II, No. 2, August 1931, and dealt with various forms of suspension clamp.

In the present article the design of tension clamps and joints is described in some detail, with special reference to those which in practice have been found to give the most satisfactory results.

THE choice of conductor tension clamps and joints for use on an overhead transmission line calls for the most careful consideration, since it is upon these fittings as much as any other items of the equipment that the safety of the line depends.

They are subject continuously to high mechanical stress, and for considerable periods carry heavy loads. These periods of heavy loading may be the outcome of low temperature and a strong wind or the formation of ice or sleet during the winter months. In addition to these loads the clamps will in all probability be subject to dynamic forces arising from conductor vibration, and since the magnitude of these forces cannot be predetermined, lengthy tests and experience are required before it can definitely be established that the fittings are suitable for the duty they have to perform.

It is unfortunately true that many engineers responsible for the design of an overhead transmission line concentrate their attention more on the safety of towers, foundations, conductors and insulators while fittings such as suspension clamps, tension clamps and joints are passed over as being equipment of secondary importance. It is well therefore always to bear in mind that the safety of conductors and towers is useless if a design of tension clamp or joint is chosen which is not fully capable of meeting all the requirements of each particular case.

Further, the designer should keep before him the fact that whereas it is possible to calculate with considerable accuracy the factor of safety of such components as towers and foundations, the safety factor of the clamps and joints cannot be predetermined since it is a matter not only of design, but of tests and experience. Even test results are not entirely conclusive because of the difficulty of simulating service loading conditions, in the laboratory, *i.e.*, vibrations, rise and fall of temperature, variation in duration and magnitude of load.

Consequently the primary considerations should be those of suitability and quality and there should be no difficulty in satisfying these from the economical standpoint since the cost of the fittings is but a small proportion of the total cost of the line.

TENSION CLAMPS.

The essential features which a good design of tension clamp must possess may be summarised as follows :—

1. The fitting must have adequate slip strength, *i.e.*, it must be capable of holding the conductor at a load which is equal or very close to the ultimate breaking strength of the conductor.
2. The clamping arrangements must not damage the surface of the conductor.
3. The clamping arrangement must ensure an equal distribution of the load over the whole section of the conductor.
4. The injurious effects of conductor vibration must be reduced to a minimum.
5. Corrosion due to electrolytic action at the points of contact of different materials must be eliminated.
6. With tension clamps which necessitate cutting the conductor inside the clamps the electric conductivity must be 100 per cent of the conductivity of the conductor itself.
7. The surfaces across which the electric current has to pass must be so designed as to avoid any increase of resistance, such as is liable to occur after long periods of service due to corrosion, local heating, etc.

In the following description some designs of tension clamps are described with particular reference as to how they comply with the main requirements mentioned above.

Tension clamps through which the conductor can be passed without cutting are shown in figs. 14, 15, and 16, while with the clamp shown in fig. 17, the conductor must be cut. The three former are suitable for use with conductors consisting of one material (copper, aluminium or steel, etc.), whereas the latter is designed for composite conductors such as steel cored aluminium.

With the clamp shown in fig. 14 the conductor is held by a number of U-bolts which press the conductor into a wavy groove in the clamp body. By this means adequate slip strength is obtained, part of the load being transmitted to the clamp body by the deviation of the conductor at the mouth of the clamp. The slip strength of this type is 95 per cent of the ultimate breaking load of the conductor, and the distribution of the load over the section of the conductor is fairly equal. In order to avoid damage to the conductor and also corrosion due to electrolytic action a tape is used consisting of the same material as the conductor.

The clamps shown in figs. 15 and 16 are designed on similar lines but, instead of U-bolts, cones are used in the design shown in fig. 15 and a wedge in the design shown in fig. 16. In these two types part of the load on the conductor is transmitted to

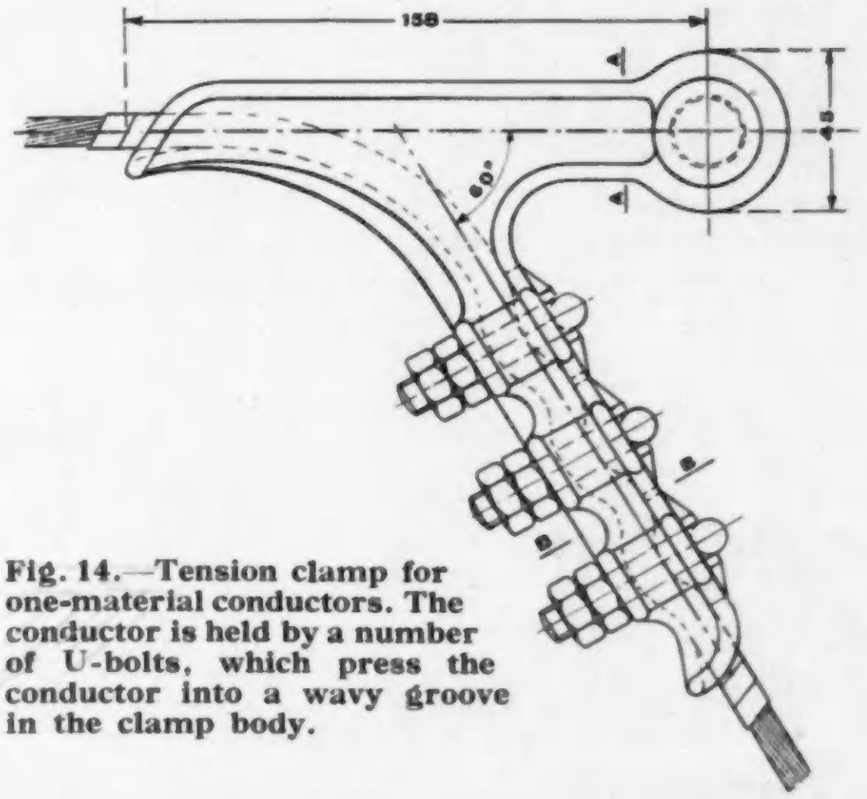


Fig. 14.—Tension clamp for one-material conductors. The conductor is held by a number of U-bolts, which press the conductor into a wavy groove in the clamp body.

the clamp body by the deviation of the conductor at the mouth of the clamp, but the main part of the load is transmitted by the cones or wedge respectively.

Advantages of these two types are that the conductor is not kinked at the clamping point, and the length of the cones and wedges respectively is such as to ensure that the clamping pressure on the conductor is comparatively small. A further advantage is that the conductor cannot work loose in service due to vibration or other causes, as the cones and wedges are held in position by nuts which are prevented from rotating by means of a locking device. Moreover, any tendency of the conductor to

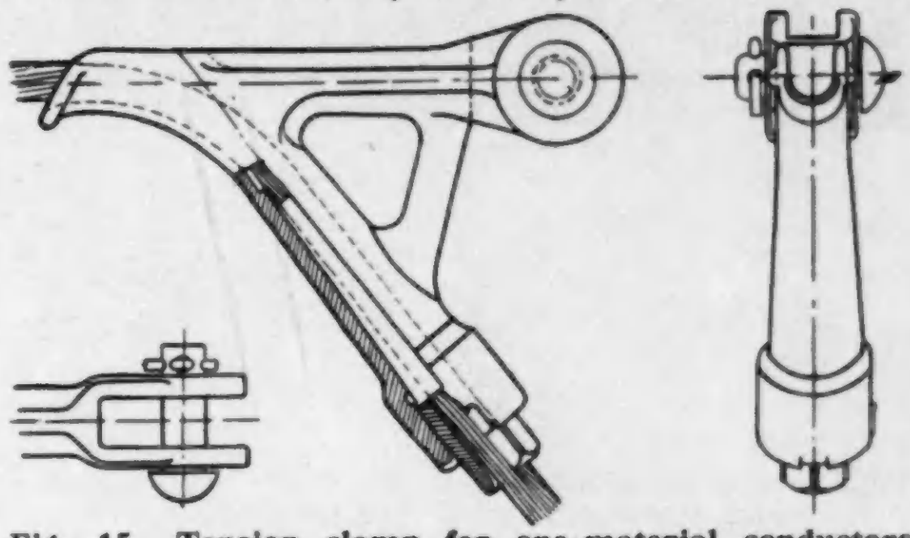
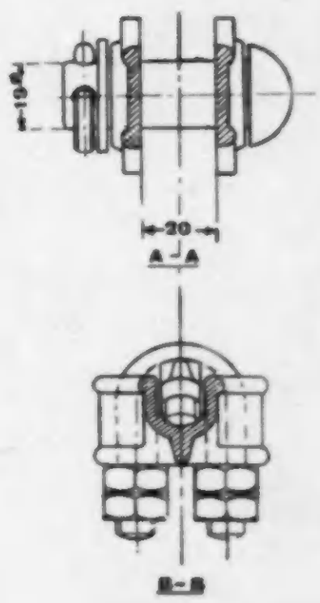


Fig. 15.—Tension clamp for one-material conductors using cones for clamping the conductor.

slip automatically results in the cones and wedges being pressed into closer engagement with the conductor.

A slip strength of 95 per cent of the ultimate breaking strength of the conductor can be guaranteed, although it is a common experience for the clamps when tested to develop 100 per cent of the ultimate strength of the conductor. The clamp body is made of galvanised malleable iron and the cones or wedges are made of the same material as the conductor.

The tension clamp shown in fig. 17 is designed for use with steel cored aluminium conductor and employs a cone system whereby the steel core and the aluminium strands are gripped separately, thus ensuring that the steel and aluminium each carries its share of the total conductor tension. The steel cones (A) are of hardened steel and transmit the load in the steel core direct to the clevis (C). The load in the aluminium strands is transmitted to the aluminium body by the aluminium cones (B) and from there to the clevis (C). The operation of the clamp can clearly be seen from the section drawing. This design is also automatic in that any tendency of the conductor to slip has the effect of increasing the grip of both the aluminium and steel cones.



As aluminium is a soft material, the design of the aluminium cones requires special care. The length and taper chosen are such as to ensure a comparatively low intensity of pressure on the aluminium wires. The inner cone is provided with serrations both on the inside and outside, the serrations being graduated from none at all at the mouth of the clamp to a maximum at the inside end.

Many tests carried out with this type of clamp have shown that it is capable of holding the conductor at 98 to 100 per cent of its theoretical breaking load. The various parts are designed for a factor of safety of 2½, based on the elastic limit of the material. The hollow spaces inside the clamp are filled with

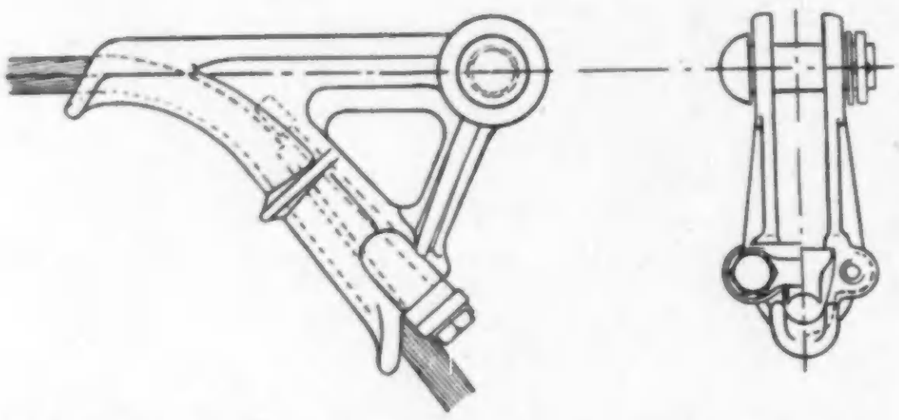


Fig. 16.—Tension clamp for one-material conductors using a wedge for clamping the conductor.

grease in order to avoid any corrosion which might result from water entering the clamp.

Unlike the two clamps previously discussed, with this type the conductor must be cut when making-off. A special cone connection (D) is provided for the jumper loop and parallel groove clamps are therefore unnecessary. The slip strength of this connection is ample even when weights are used on the jumper to limit its swing under transverse wind load.

The question of electrical conductivity needs careful consideration since it by no means follows that because the conductivity of a clamp is satisfactory at the time of erection it will continue so

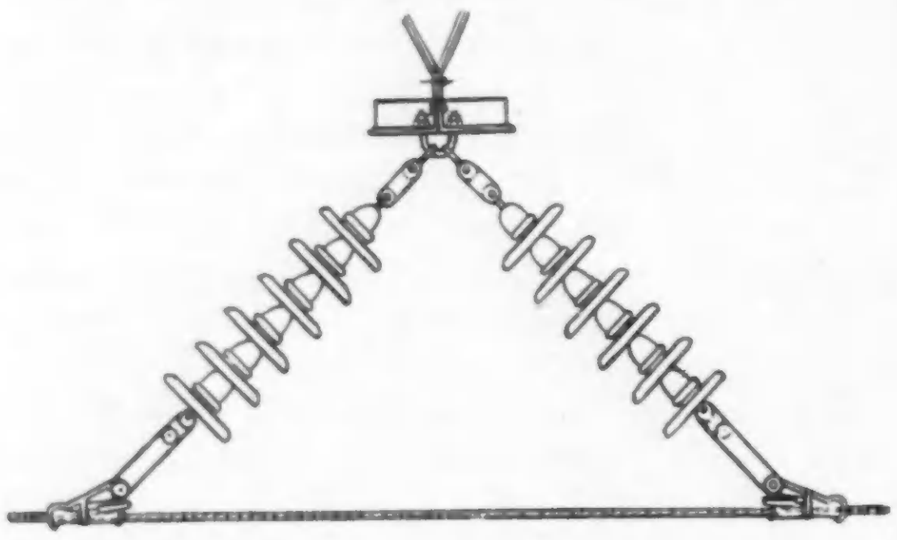


Fig. 18.—Semi-anchor clamps in use.

throughout its life. Indeed, cases have been known in which the conductivity of tension clamps has so deteriorated in the course of years that the consequent heating of the fittings has necessitated their replacement. Investigation has shown that these troubles are due to the current having to pass across a screw thread.

In the clamp shown in fig. 17, the current passes from the aluminium wires of the conductor *via* the cones (B) to the body (E) and thence *via* the cones (D) to the jumper loop conductor. It will thus be seen that the current in its passage through the clamp traverses large smooth surfaces in intimate contact and avoids threaded parts entirely. Consequently, the conductivity is at least equal to that of the conductor itself.

In order to avoid damage to the conductor at the

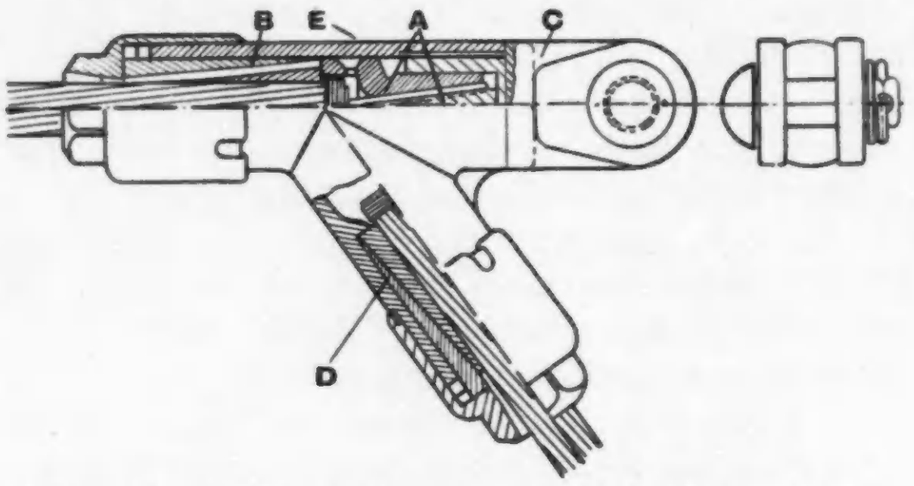


Fig. 17.—Tension clamp for composite conductors.

tension clamp due to conductor vibrations, not only must the weight of the clamp be kept to a minimum but also the distance between the mouth of the clamp and the point of attachment must be as short as possible. Further, the pivot point of the clamp should be on the centre line of the conductor.

The shorter and lighter the clamp, the more readily can it follow the vibrations of the conductor and the more nearly will the node point of the vibration wave coincide with the point of attachment, thus avoiding additional bending stresses in the conductor at the mouth of the clamp.

With long and heavy clamps as for instance the multi-bolted type for steel cored aluminium conductor, it is found that under vibration of high frequency, nodes are formed near the mouth. It is also noticeable that this clamp does not vibrate in

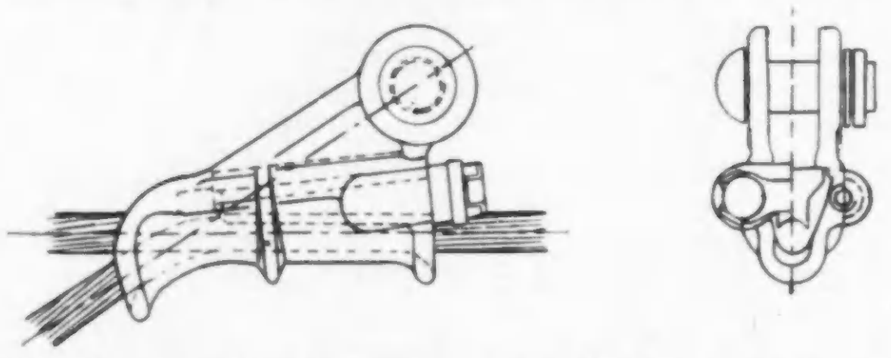


Fig. 19.—Semi-anchor clamp capable of acting as a tension clamp in emergencies.

phase with the conductor. These conditions cause heavy bending stresses in the strands of the conductor which lead to fatigue failures.

From these considerations the clamps shown in figs. 14 to 17 should be immune from vibration troubles and this is borne out by the results of a series of tests carried out at the G.E.C. Research Laboratories at Wembley. The following is typical :—

1. *Type of Conductor*—Steel-cored aluminium

.175 sq. in. copper equivalent, 30/.11 inch aluminium. 7/.11 inch steel.

2. *Length of conductor tested*—100 ft.
3. *Tension in conductor*—8,000 lbs.
4. *Frequency of vibration*—1,000 per minute.
5. *Amplitude*—2 inches.
6. *Number of vibrations*—5,000,000 without damaging conductor.

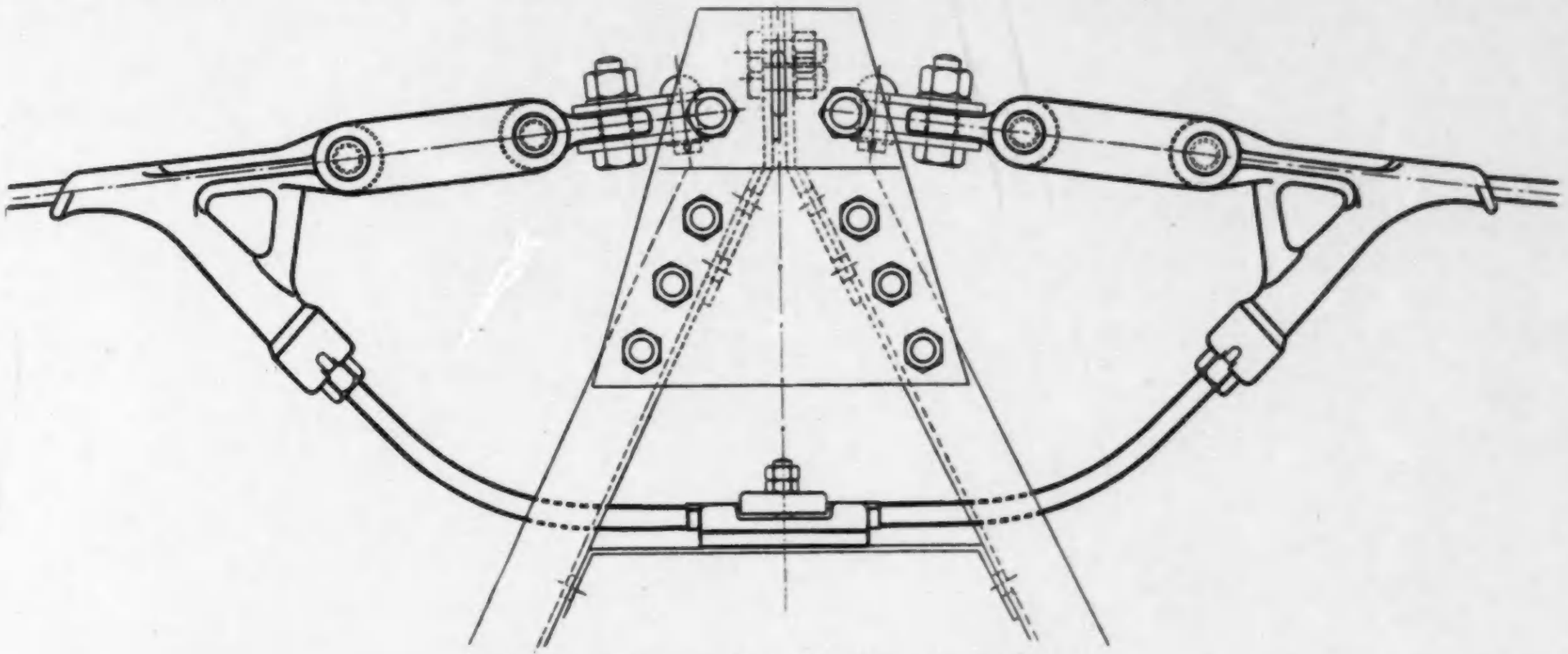


Fig. 20.—Earth conductor tension arrangement.

The above test conditions are far more severe than the worst likely to be encountered in practice and were deliberately chosen in order to carry out what amounts to a life test in a short time.

Further valuable information may be found in a paper read before the Institution of Electrical Engineers by Mr. P. J. Ryle: "Two Transmission Line Problems—Suspension Insulators for Industrial Areas in Great Britain—Conductor Vibration," Vol. 69, No. 415, page 820.

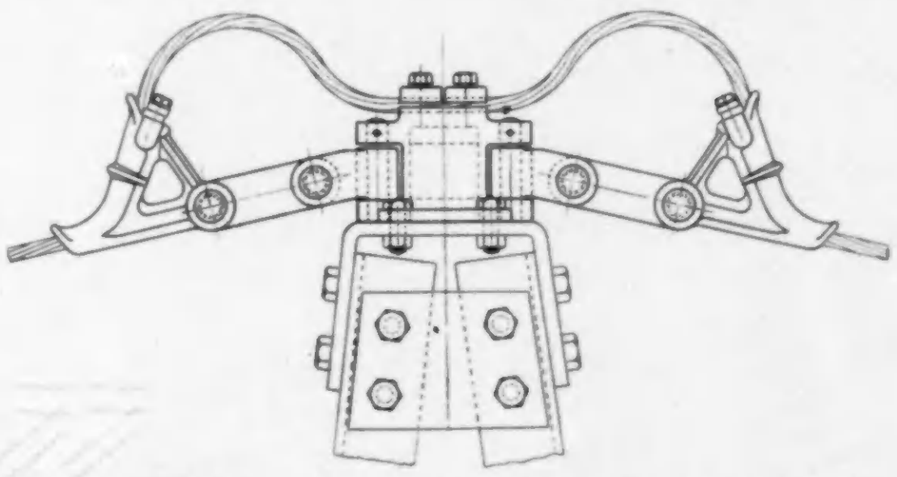


Fig. 21.—Earth conductor tension arrangement employing two wedge type tension clamps.

SEMI-ANCHOR CLAMPS.

It is common practice in some countries to make use of the "semi-anchor" arrangement (see fig. 18) of the conductors at points on the line, such as road and railway crossings, where a higher safety is desirable. Two insulator strings are suspended on a standard straight line tower at an angle of 45°. Normally the two strings act as suspension strings but under broken conductor conditions in one span the string in the adjacent span acts as a tension string and prevents the conductor from falling to the ground, and also avoids any undue increase of sag. A semi-anchor clamp must therefore be capable of

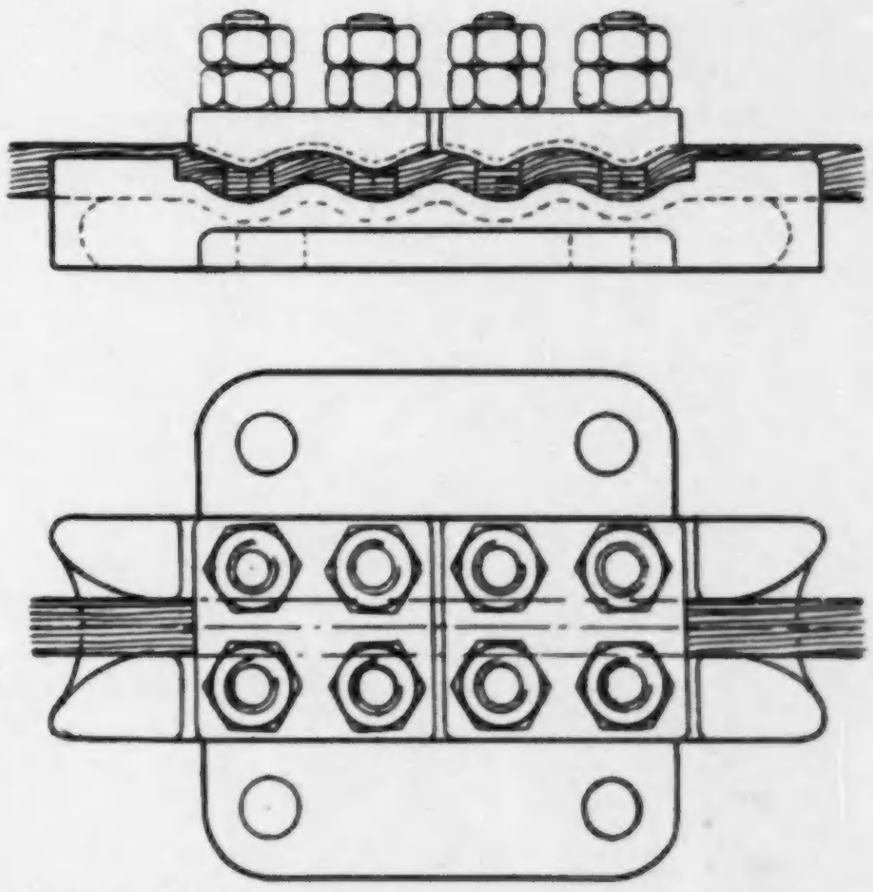


Fig. 22.—Simple earth conductor tension clamp for use with steel, copper or bronze conductor.

acting as a tension clamp in emergency and it must be of a type which does not necessitate cutting the conductor or threading it through when erecting.

The clamp shown in fig. 19 complies with these main requirements and is made in two types, large and small. The larger is employed with steel cored aluminium conductor and the smaller in

conjunction with copper or steel conductor. The body of both types is of malleable iron and the wedges of similar metal to the conductor they have to grip. The slip strength of these clamps is about 90 per cent.

Fig. 23.—Simple jointing arrangement consisting of two one-part screw joints.

EARTH CONDUCTOR TENSION CLAMPS.

The tension clamps described at the beginning of this article are equally suitable for use with an earth conductor. A general earth conductor tension arrangement is shown in fig. 21 employing two normal wedge type tension clamps and a special tension fitting which is secured to the apex of the tower by four bolts.

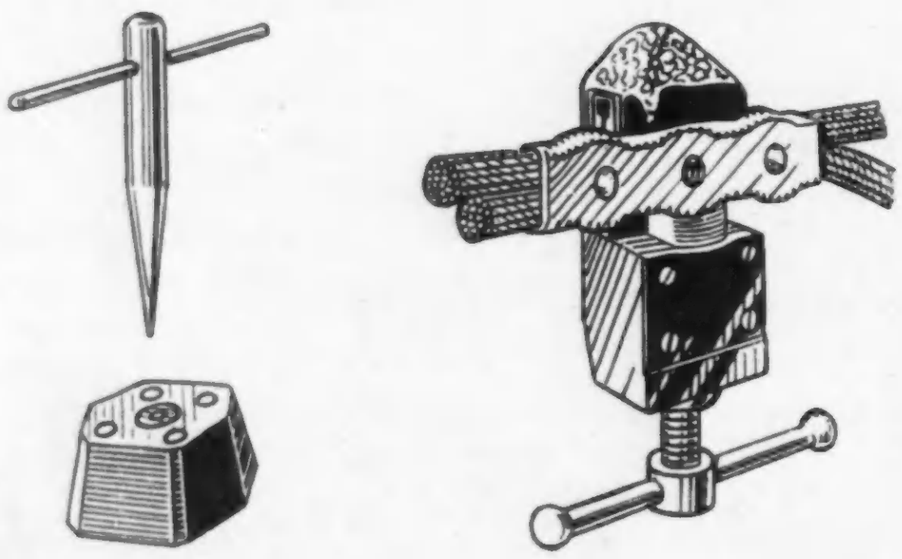


Fig. 24.—Special tools for assembling screw joints.

It will be seen that the special fitting is provided with swivels which allow the tension clamps to oscillate either vertically or horizontally. It also incorporates a bonding clamp which ensures good electric contact between the earth conductor and the tower and also serves as a parallel groove clamp in the case of tension clamps which call for a connection to be made in the jumper.

Another earth conductor tension arrangement is shown in fig. 20, from which it will be seen that the tension clamps are coupled by extension links to swivels attached direct to the tower. The special tension fitting described above is not used in this arrangement and a separate bonding clamp must therefore be employed.

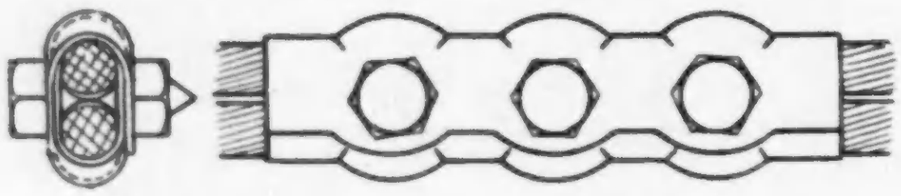


Fig. 25.—Two-part screw joint.

Fig. 22 shows a very simple earth conductor tension clamp which however can only be recommended for use with steel, bronze or copper conductor on lines of secondary importance.

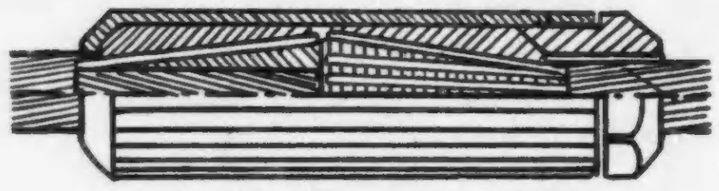


Fig. 26.—Cone type joint.

JOINTS.

As a conductor joint is, in effect, a combination of two tension clamps back to back, the essential features which a good joint should possess are the same as those for a tension clamp.

One of the simplest jointing arrangements is that shown in fig. 23. The sleeves should be of the same material as the conductor in order to avoid corrosion due to electrolytic action. They are so shaped that when the pointed screws are inserted the conductor is forced into the side cavities and assumes a wave form.

Where it is not possible to thread both ends of the conductors to be joined through the sleeve, a two-part screw joint (fig. 25) must be employed. This fitting is therefore useful for securing an auxiliary to a main conductor, as for example at road and railway crossings, where the conductors must either be duplicated or provided with bridles in accordance with the regulations. Two of these screw joints in series will develop 95 per cent of the ultimate strength of the conductor and will give 100 per cent conductivity.

It should be mentioned that special tools (fig. 24) are required for assembling the screw joints and the action of these will be apparent from the illustration.

For the more important lines a joint working on the cone principle (fig. 26) is to be preferred.

It should be emphasised, in conclusion, that the above joints are only suitable for use with conductor consisting of one material. For composite conductors such for example as steel cored aluminium a joint must be used which grips each component separately. A joint of this type is shown in fig. 27, from which it will be seen that the principle is similar to that of the tension clamp illustrated in fig. 17. It is advisable to avoid the use of castings and for this reason the outer tube forming the body of the joint should be made of hard drawn aluminium.

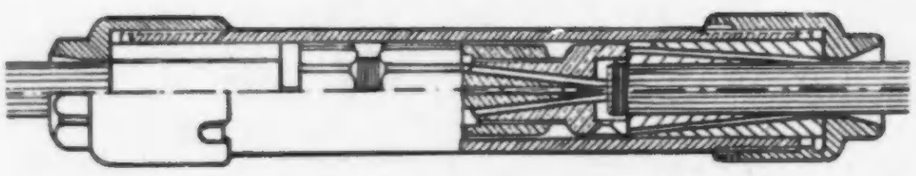


Fig. 27.—Special cone type joint for composite conductors.